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Exploring the Universe with the
**Hubble
Space
Telescope**



Cone Nebula in Monoceros
(Anglo-Australian Observatory)

NASA
National Aeronautics and
Space Administration

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From our home on the Earth, we look out into the distances and strive to imagine the sort of world into which we are born. Today we have reached far out into space. Our immediate neighborhood we know rather intimately. But with increasing distance our knowledge fades, and fades rapidly, until at the last dim horizon we search among ghostly errors of observations for landmarks that are scarcely more substantial.

The search will continue. The urge is older than history. It is not satisfied and it will not be suppressed.



Edwin P. Hubble
Astronomer



We are stargazers.

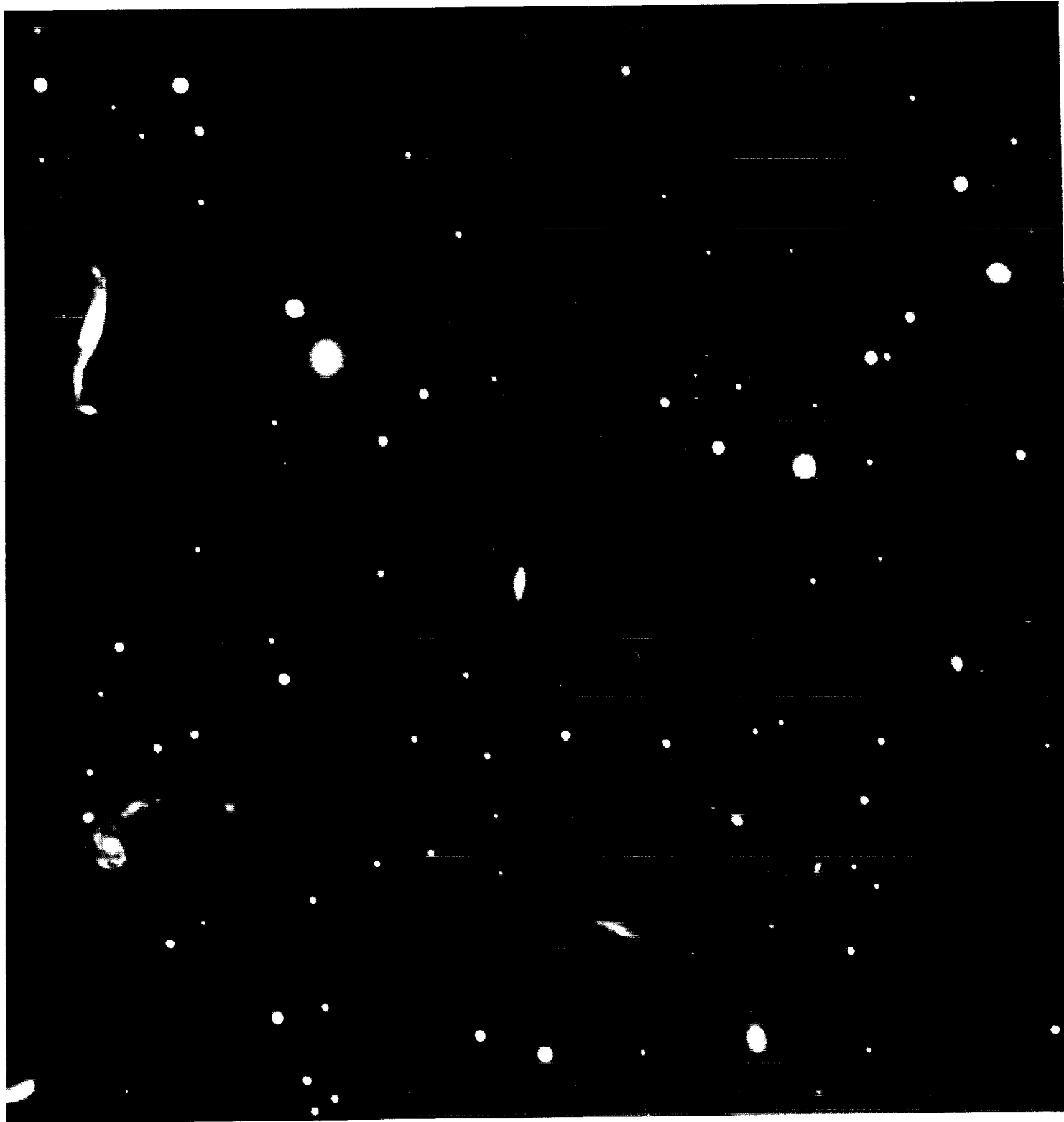
A child pointing with delight to the first star at twilight, a rooftop amateur with telescope scanning the night sky, an astronomer dwarfed by the mirror in a silent observatory on some dark, remote mountain peak—

everyone searches the heavens. What is it that we seek?

Astronomy has captured our imagination as perhaps no other science, for it embraces such incomprehensible size and distance and time

that we can barely ponder it. We think that the universe originated some 15 billion years ago, but who, in an average life of only 70-odd years, can conceive of such eternity? We estimate that our galaxy contains about two hundred billion stars and that it is only one of more than a

hundred billion galaxies, so there must be some twenty thousand billion billion stars in the universe; the mind balks at such incredible numbers. We who measure distance in miles and kilometers struggle with the concept of a single light year, almost six trillion miles,




much less cosmic distances counted in millions and billions of light years. Astronomy stretches our minds and invites us into the realm of the imaginary.

When we look to the heavens, we are not only awed by the immensity of time and space; we also

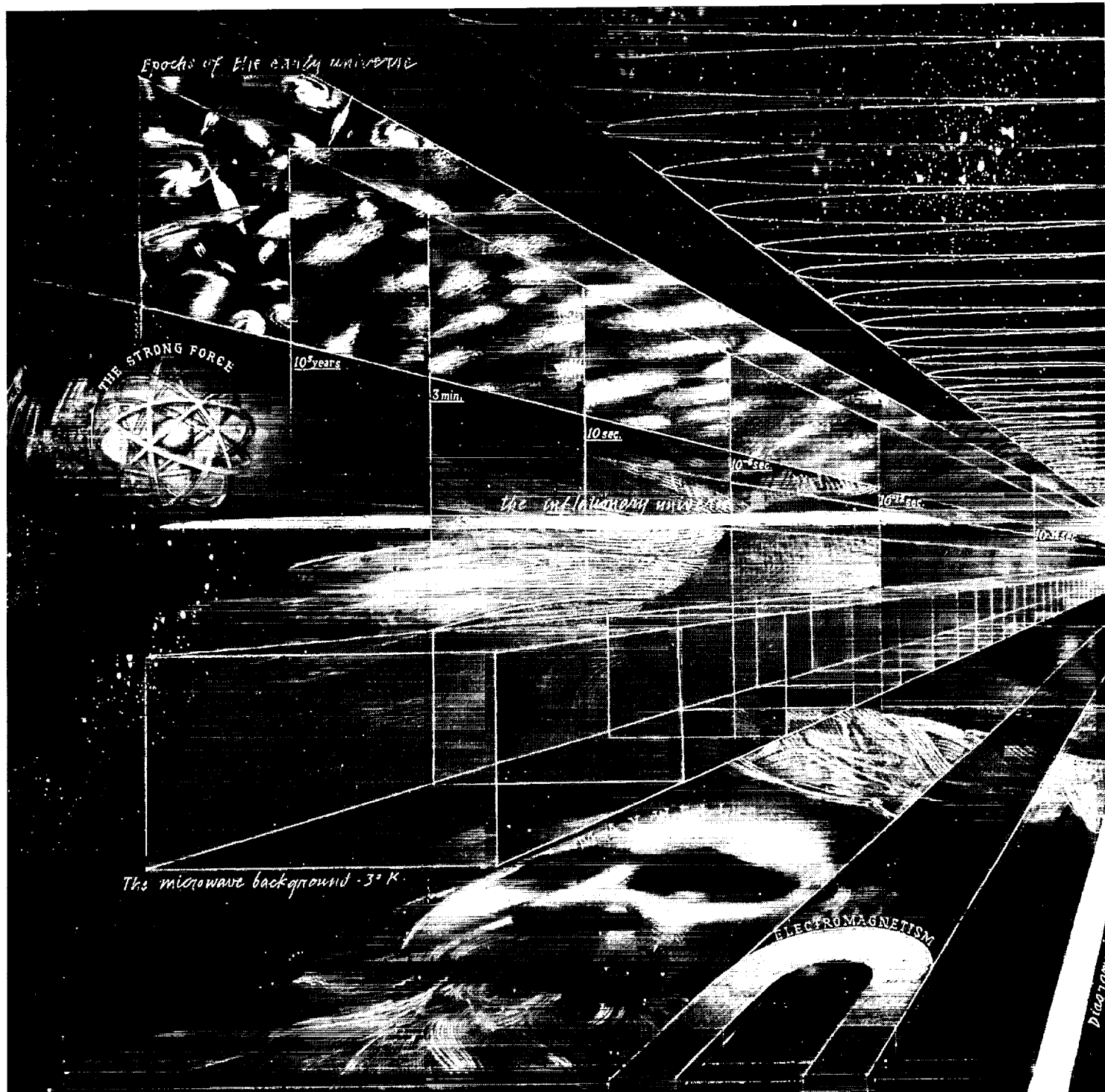
learn something. Starlight is information. In the stars and galaxies, we gain clues to the origin and history of the universe and we begin to understand the exquisite patterns of the cosmos. All that we know about the universe, we know from observing.

Today, we are on the verge of exciting discoveries as a new observatory is prepared for use. The Hubble Space Telescope, an orbital observatory designed to probe the universe with extraordinary precision and clarity, much farther than we have ever seen, will dispel much of

the mystery and uncertainty that limit our knowledge. As we repeat the age-old act of stargazing, the wonder and beauty of the universe will be revealed anew, astonishing us again as it surprised Galileo when he first used a telescope almost 400 years ago. 

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Cluster of Galaxies in Hercules (Kitt Peak National Observatory)



First Light

In a flash of light, the universe came into being. The dark abyss suddenly filled with energy and matter and motion. From this colossal explosion, an expanding wave of infinite reach surged into time and space. In its wake are strewn the galaxies, stars, and planets—the wondrous creation we call the cosmos.

In those first moments, some 15 billion years ago, events happened so rapidly and forcefully that no evidence lingers, except a faint background radiation. Within the first three minutes, the rudiments of matter appeared in the expanding fire-



The Big Bang. Barron Storey. 83

The Big Bang (Barron Storey, artist; © National Geographic Society)

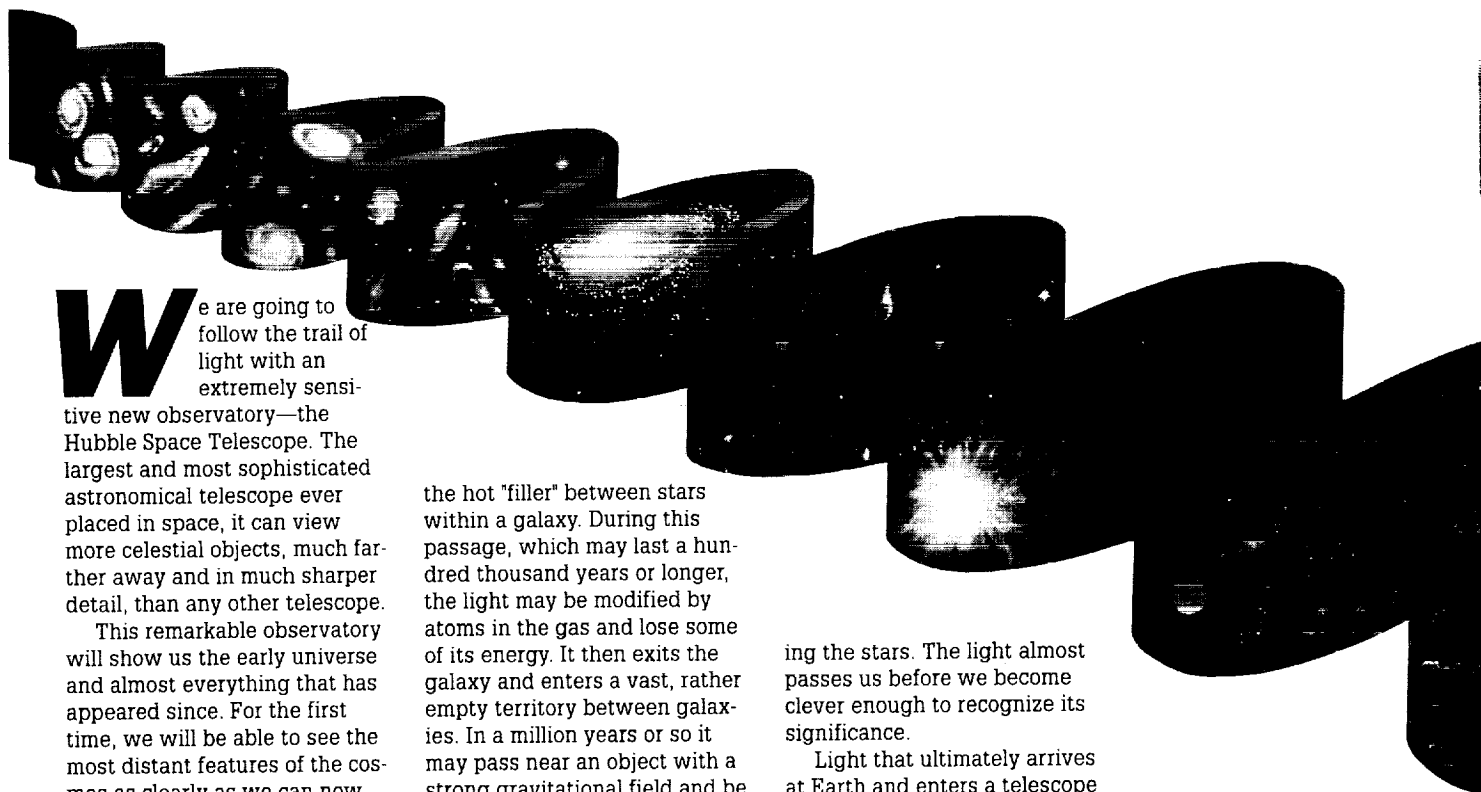
all of intense radiation. About 100,000 years later, hydrogen formed in the cooling maelstrom, then helium and some of the other elements. These atoms began to circulate through the primordial gas and clump together into whirling masses that eventually took shape as

galaxies. Exactly when the first galaxies appeared is unknown, but the answer may lie in very distant quasars, more than 10 billion light years from Earth. Within the galaxies, billions upon billions of stars began to shine, and around at least one star a system of planets coa-

lesced, one of which is our home.

The mystery of it all has engaged philosophers and priests, scientists and stargazers from time immemorial. Of course, no one was there to witness the beginning. There are no historical records, no on-the-scene reports. All we have to guide us

toward understanding is light. Light is the messenger of creation, a cosmic courier bearing the evidence. The evanescent trail of light from the present back to the first moments carries all the information we will ever have about the origin of the universe.



We are going to follow the trail of light with an extremely sensitive new observatory—the Hubble Space Telescope. The largest and most sophisticated astronomical telescope ever placed in space, it can view more celestial objects, much farther away and in much sharper detail, than any other telescope.

This remarkable observatory will show us the early universe and almost everything that has appeared since. For the first time, we will be able to see the most distant features of the cosmos as clearly as we can now see the nearer stars and galaxies. As we use the Hubble Space Telescope to intercept and interpret the messages carried in light, the prospects for discovery are exciting.

Astronomy is not really the study of stars; it is the study of starlight. We come to know the universe by capturing starlight as it passes by on its voyage through the cosmos, bringing it into focus and examining it.

Where has starlight been, and what can it tell us about the universe? Imagine a beam of light, emitted from an early galaxy, perhaps 10 billion years ago. Upon departing from the stars that produced it, the light flows through interstellar gas,

the hot "filler" between stars within a galaxy. During this passage, which may last a hundred thousand years or longer, the light may be modified by atoms in the gas and lose some of its energy. It then exits the galaxy and enters a vast, rather empty territory between galaxies. In a million years or so it may pass near an object with a strong gravitational field and be bent from its course, or it may wander into a dense cloud of dust left over from a star's formation and be absorbed, never to be seen.

While light is in transit, cosmic history marches on. For eons, our own part of the universe does not yet exist. The Milky Way galaxy takes shape about three billion years after the light begins its voyage. About two billion years later, the Earth condenses out of the gaseous nebula surrounding our young sun. It is another billion years before signs of life appear on our planet, and several billion more before human civilization arises and becomes capable of thoughtfully observ-

ing the stars. The light almost passes us before we become clever enough to recognize its significance.

Light that ultimately arrives at Earth and enters a telescope to be collected and magnified and guided into the eye, a camera, or other detector bears the marks of both its origin and its voyage. Its original energy and path may be altered by conditions in the space environment, but light has a message and a signature. Thus, light tells us about conditions at its source (What is the star composed of? How hot is it?) and along its way (What makes up the gas between stars in galaxies? How strong is the embedded magnetic field?). Light also brings us news of changes in the cosmos: the birth and spectacular death of stars, galaxies in collision, and the demise of stars being devoured by their neighbors.

Although the speed of light is the fastest possible way to cover distance, the distances in the universe are so great that it takes even light a very long time to reach us—millions and billions of years. A light year, the distance light travels in one year, is about 6 trillion miles. The light we receive today from the most distant object actually was emitted long, long ago when the universe was very young.

Thus, detecting light from distant objects is looking back in time, seeing the universe as it was when the light left the objects, not as it is now.

Some 12 to 20 billion years ago, astronomers think a "primeval atom" exploded with a big bang sending the entire universe flying out at incredible speeds. Eventually matter cooled and condensed into galaxies and stars. Planets formed around at least one star. Eons after life began to develop on Earth, humans appeared. If all events in the history of the universe until now were squeezed into 24 hours, Earth wouldn't form until late afternoon. Humans would have existed for only two seconds.



(Jaime Quintero, artist; © National Geographic Society)

Astronomy through the Ages

To study the universe, its history and its contents, we use whatever we can to catch and analyze light. The most common tool for astronomy is the eye. When we look up at the sky, our eyes receive light, form an image, and send a signal to the brain for processing. Virtually everyone can use this "instrument"; for millennia, it was the only one available.

Unfortunately, the eye is limited in sensitivity and can perceive only the brighter celestial objects. The patient observations of early astronomers yielded an atlas of the universe visible to the unaided eye. They charted the motions of the planets, recorded the positions of many stars, and witnessed a few spectacular explosions of dying stars. However, they had no inkling of the universe we can observe today.

About 400 years ago, Galileo wedded technology and astronomy by using a telescope, a piece of equipment to enhance human vision. His simple arrangement of two magnifying lenses in a tube enabled the

first detailed look at some of the objects in the sky and multiplied the number of visible stars. The moon, previously seen as a mottled disk of light and darker

patches, suddenly showed a terrain of mountains and valleys. Four of Jupiter's moons were revealed, and stars "so numerous as to be almost beyond belief."

Technology made a world of difference in our ability to form images. The history of astronomy since Galileo's time is a history of technological advances leading to discoveries. Progress in astronomy depends on improved telescopes and detectors to supplement the eye.

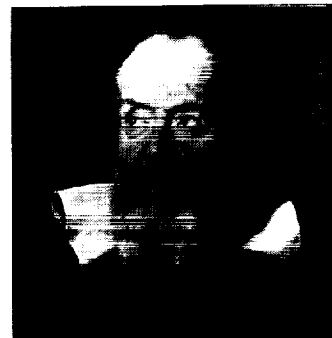
Over the past four centuries, larger and larger mirrors have been constructed for reflecting

telescopes. The larger the mirror, the more light is collected and focused into the image. One result is brighter images; objects that were previously below the threshold of detection are now "seen." Another result of using larger mirrors is enhanced fineness of detail (resolution) that can be seen in the image; images are sharper, containing more detailed information.

For collecting light and forming sharper images, bigger is better. Thus, observatories vie for pre-eminence on the basis of mirror size, graduating from mirrors the size of coins and dinner plates to disks as large as backyard satellite dishes. Improvements in mirror grinding, polishing, and reflective coatings also have made a difference.

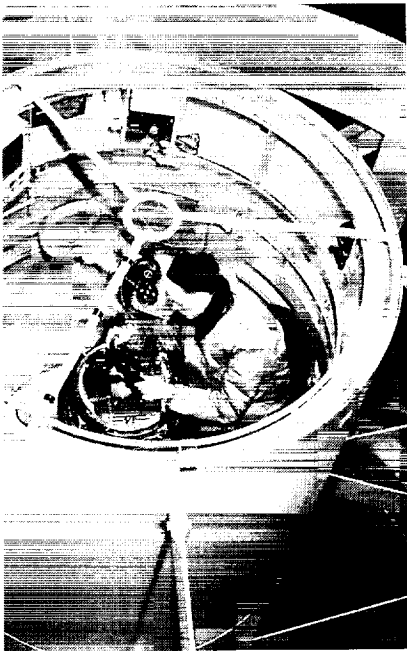


Amateur astronomers and home-made telescopes
(Dennis di Cicco)



Galileo, credited with first use of the telescope in 1609
(Yerkes Observatory)

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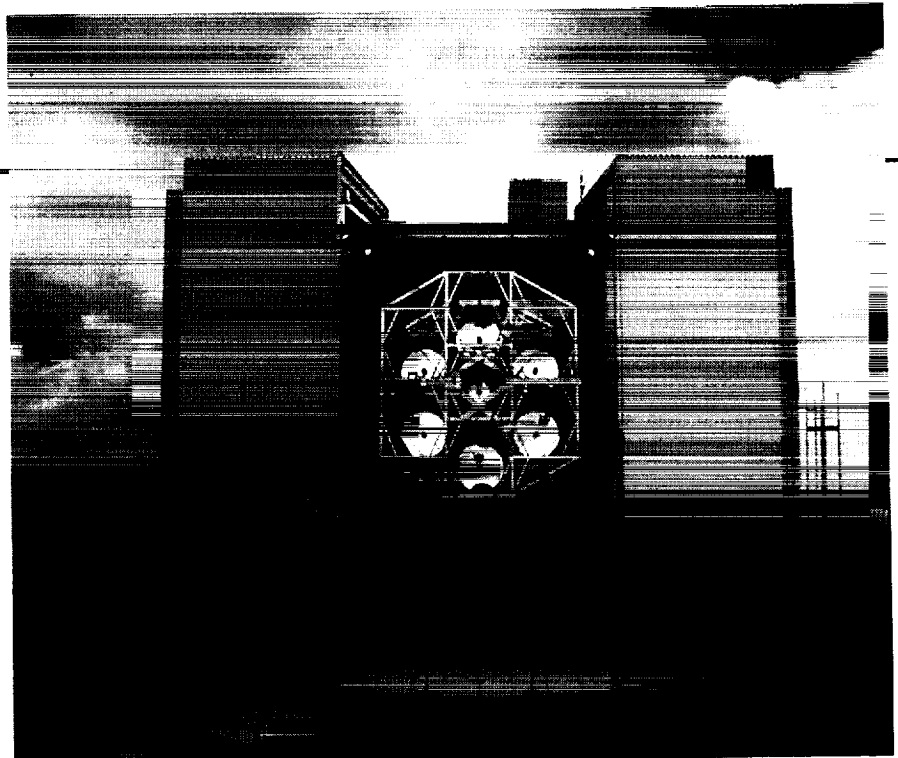
**Astronomer in observing capsule
of the 200-inch Hale telescope**
(Palomar Observatory, California Institute of Technology)

In the past century, and especially during the last 50 years, advances in detector technology have influenced progress in astronomy even more than mirror size. Putting a camera, rather than an eye, at the viewing end of a telescope makes it possible to record more light and preserve the image for analysis. Increasingly sensitive photographic films and longer exposures are bringing very faint celestial objects into the range of detectability. New electronic systems capable of recording individual photons are now displacing film as the detectors of choice for imaging faint (distant) astronomical objects.



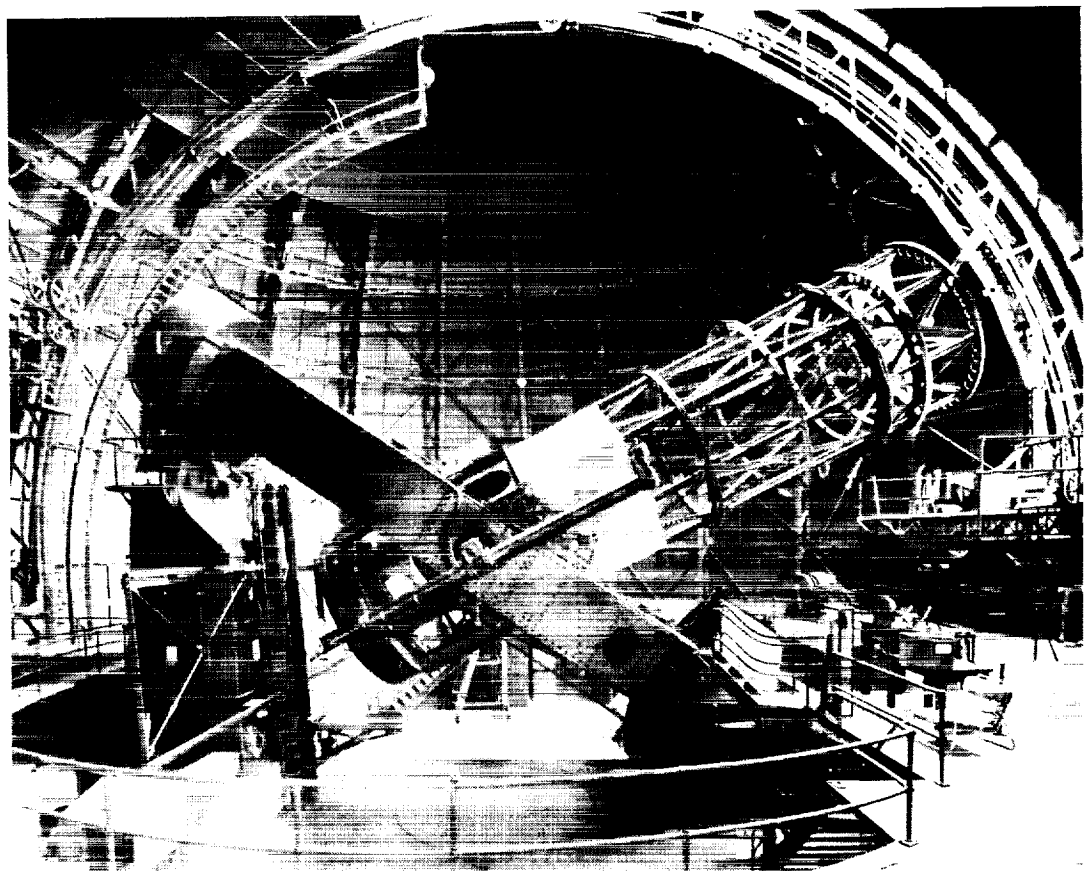
**Astronomer Annie Cannon, early
20th-century pioneer in spectral
analysis** (Harvard College Observatory)

**100-inch Hooker telescope
at Mount Wilson**
(California Institute of Technology)



**The Multiple Mirror Telescope at Mt. Hopkins, Arizona—
an innovative design for a large light-collecting surface**
(MMT Observatory)

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Advances in mirror and detector technology yield dramatic improvements in obtaining information about objects in the sky, up to a point. Then astronomers face a barrier that is not affected by bigger, more sensitive telescopes: the atmosphere. Despite centuries of observing, we have not yet seen

the universe clearly, because we are looking up through a hazy shroud of gases around our planet. As light from celestial objects is bent, scattered, and absorbed by passage through our turbulent atmosphere, images are distorted, blurred,

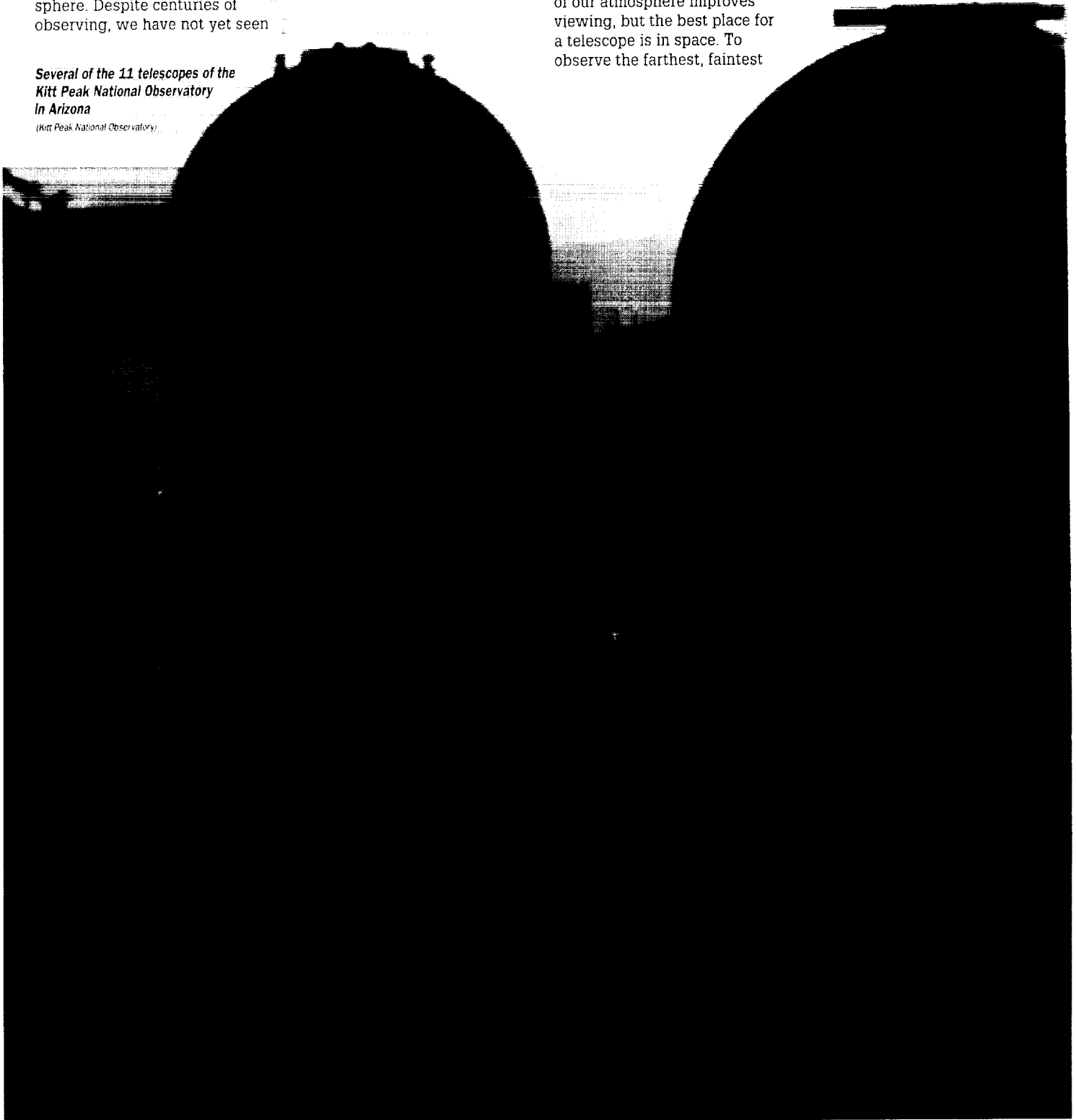
and dimmed. From the ground, we can distinguish objects well only to a distance of some two billion light years, although the universe probably extends ten times farther.

Placing telescopes on high mountain peaks above part of our atmosphere improves viewing, but the best place for a telescope is in space. To observe the farthest, faintest

stars and galaxies in as much detail as possible, we must lift our telescopes into orbit beyond the turbulent, obscuring atmosphere. If it were practical, most telescopes would be located in space, where viewing conditions are most favorable.

**Several of the 11 telescopes of the
Kitt Peak National Observatory
in Arizona**

(Kitt Peak National Observatory)



**The Hubble Space Telescope
during assembly and testing**
(Lockheed Missiles and Space Company)

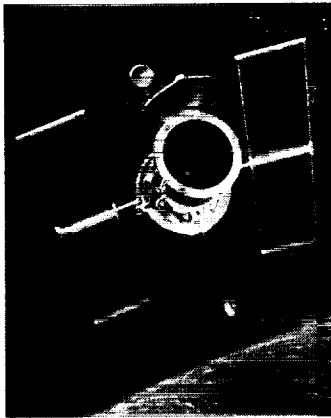
Astronomers have dreamed of placing a large visible-light telescope into space, but only recently has the technology been developed to make this possible. The Space Shuttle is powerful enough to carry into orbit a large telescope comparable to some of the best telescopes on the ground. Furthermore, the Shuttle can take a maintenance crew to an orbital observatory for repairs and servicing. For the first time in the space age, we have a

warranty for a long operational life. Space telescopes are expensive; to get the most science from our investment, we must be able to use them for many years.

The Hubble Space Telescope is the realization of that dream: a virtually perfect mirror, superior detectors, and an orbit above the atmosphere. This is the instrument that will reveal what lies beyond our present power to see. Until now, advances in telescope capability have

occurred in fairly small steps; mirror sizes have doubled or tripled, and improvements in sensitivity and resolution have been measured up to 50 times better. With a telescope in space, we leap to new capabilities at least 10 times better than optical telescopes on the ground. The Hubble Space Telescope is the best optical telescope in the world, a precious international resource for satisfying our human need to know the cosmos.





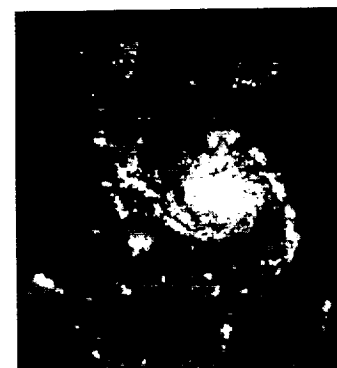
Observation Strategy

For generations, humans have looked at the same sky, asked the same questions, and pressed against the same physical barriers to observation. How large and how old is the universe, and how do we measure it? What are the objects we see there? How do galaxies form and evolve? What is the life cycle of stars? Do other planets exist? Is there life elsewhere in the universe? At first, our attempts to explain the cosmos took the form of myths and folklore, which have now given way to scientific theories and observations.

Of all the observatories that exist in the world, only the Hubble Space Telescope can answer some of the most perplexing astronomical questions. The Hubble Space Telescope can detect objects 12 to 14 billion light years distant as clearly as a much larger telescope on

the ground can detect objects a mere 1 to 2 billion light years away. Images will be at least 10 times sharper in clarity than any others, and light emitted very early in the life of the universe, 30 to 50 times fainter than our current threshold, will be easily detected.

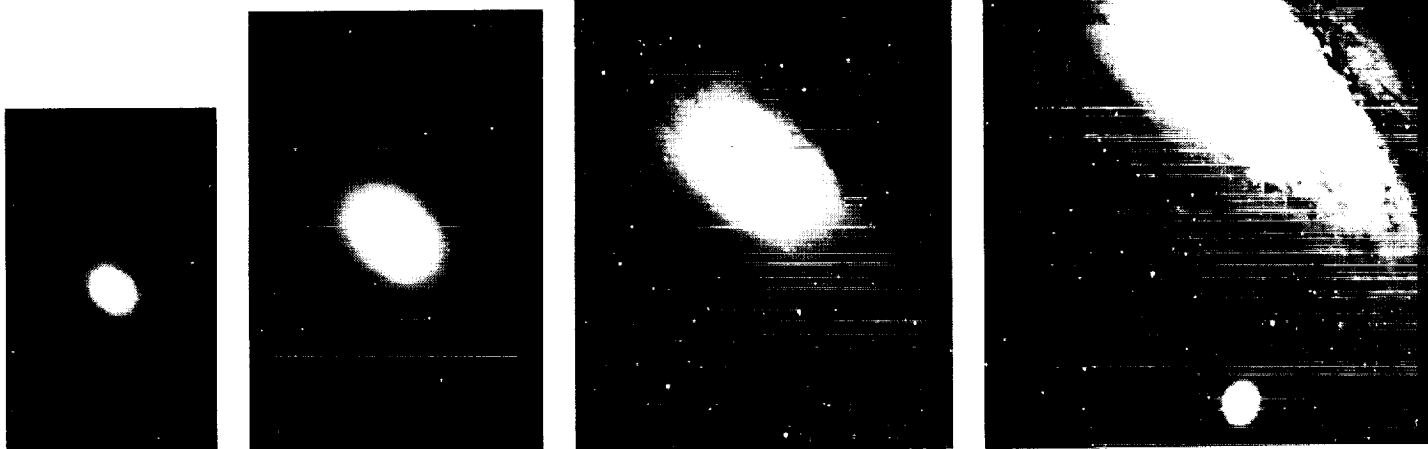
The observing strategy takes advantage of these unique abilities to see objects farther away and with greater clarity than any other telescope. The highest priority investigations are those that cannot be performed from the ground; we do not know exactly what these exploratory observations will reveal. Some are focused where our knowledge is quite limited, at objects beyond 10 billion light years, toward the "edge" of the observable universe. Research requiring extraordinarily precise position measurements, now possible for the first time, is scheduled early in the



These images of M101 galaxy in Ursa Major, one 10 times sharper than the other, simulate the improvement in detail expected in images from the Hubble Space Telescope. (California Institute of Technology)

In longer time exposures, more light is collected and resulting images have more detail. These images of two galaxies in Andromeda resulted from observations lasting 1 minute, 5 minutes, 30 minutes, and 45 minutes, respectively. The Hubble Space Telescope will be able to obtain detailed images of faint objects with shorter exposures than observatories on the ground.

(Kitt Peak National Observatory)



lescope's mission. Another high priority is examination of the ultraviolet radiation from celestial objects, radiation that cannot be observed from the ground.

The "eye" of the Hubble Space Telescope will be turned upon both familiar and exotic objects, neighboring areas in space and the farthest territories. Producing images at a rate of about 20 a day, we should have more than 7,000 images a year and, over its planned 5-year operation, more than 100,000 pictures as enthralling as those from the planetary explorers. The information in these images is the source material for discoveries.

Observation is exploration. Because we cannot yet venture into the far reaches of time and space, we have to explore by collecting radiation. With the Hubble Space Telescope, we have the opportunity to see and know more about the universe. This observatory, perhaps more than any other, appeals to our imagination with the promise of new knowledge, beautiful images, and answers to the most intriguing questions.

The Hubble Space Telescope may answer questions about all classes of astronomical objects, from neighboring planets and stars to the most distant galaxies and quasars.

Victor Costanzo, Jr., and Brian Sullivan, artists



Edwin P. Hubble

1889–1953

As a child, Edwin Powell Hubble wandered the Kentucky countryside where he grew up, observing the habits of birds and animals. As an adult, he scrutinized the stars and galaxies.

Although Hubble was always interested in science, he did not settle on the profession of astronomy immediately. In 1910, he received an undergraduate degree from the University of Chicago, where he also lettered in basketball and almost became a professional boxer. Instead, he studied law under a Rhodes scholarship at Oxford, passed the bar, and practiced law briefly and halfheartedly. He reported that he “chucked the law for astronomy, and I knew that even if I were second-rate or third-rate, it was astronomy that mattered.”

Hubble completed graduate studies at the Yerkes Observatory of the University of Chicago, where he began his examination of spiral nebulae. He earned his doctorate in 1917 and was invited to join the Mount Wilson Observatory in Pasadena, California, but Hubble did not yet undertake the studies that made him famous. Answering the call to World War I, he enlisted in the infantry, telegraphing observatory personnel, “Regret cannot accept your invitation. Am off to the war.”

Two years later he finally began working with the tool that would enable him to make great discoveries—the 100-inch reflector at Mount Wilson, at the time the largest telescope in the world. Except for four years of service in World War II, Hubble was devoted to astronomy until his death in 1953.

Hubble’s patient, painstaking observations revealed a much larger universe than anyone had imagined. He was enchanted by dim, foggy patches called “nebulae,” the Greek word for cloud. One called Andromeda was the most spectacular nebula observed during the early decades of the century, but telescopes were not powerful enough to see if it harbored any stars like the vast stellar populations of the Milky Way. Since the 18th century, scientists had argued whether these areas were “island universes,” separate galaxies, or simply nebulae in our galaxy. Was the Milky Way the only galaxy? Was it the center of the universe?

In 1924, Hubble ended the debate when he reported stars in the outskirts of Andromeda and found Cepheids, stars that reveal

their distance by the way their light varies. Careful observations of the Cepheids enabled him to measure the distance to Andromeda, far too many light-years away to be in our galaxy. He classified the galaxies, grouping them by sizes and shapes, and established that many other nebulae were also galaxies even more distant than Andromeda. Hubble measured the depths of space out to 500 million light years, distances farther than any previous surveys.

As he continued to study galaxies, he concluded that they were moving away from Earth at velocities proportional to their distances. This supported the concept that the universe originated in a cosmic explosion, and all the matter in the universe was expanding from the site of an initial Big Bang. The galactic survey resulted in Hubble’s law: the more distant the galaxy from Earth, the faster it moves away.

Of course, if all the galaxies originated from one explosion, residents of other galaxies would see the same thing: a universe of fleeing galaxies with more distant ones moving more rapidly.

Hubble found that the ratio of the velocity of receding galaxies to their distance from Earth is constant (the Hubble constant), a significant astrophysical number still not calculated with certainty today. Unfortunately, as the distances to objects increase, astronomers are overwhelmed

with uncertainties: distances are hard to measure. Current estimates of the Hubble constant, and thus the rate of expansion of the universe, differ by a factor of two. More powerful telescopes are needed to make more precise measurements and determine whether the universe will expand forever or halt and perhaps reverse.

The Hubble Space Telescope will build on Hubble’s research, measuring distances with greater accuracy than ever before possible. It is fitting that this premier space observatory is named for the American astronomer whose work revolutionized modern astronomy. Hubble’s research proved that larger, more powerful telescopes are needed to see more of the universe. He assisted in the design of the 200-inch Hale telescope at Mount Palomar near San Diego and made the first observations with it. When asked what he expected to find with the new telescope, he said, “We hope to find something we hadn’t expected.” With the Hubble Space Telescope, this quest continues.

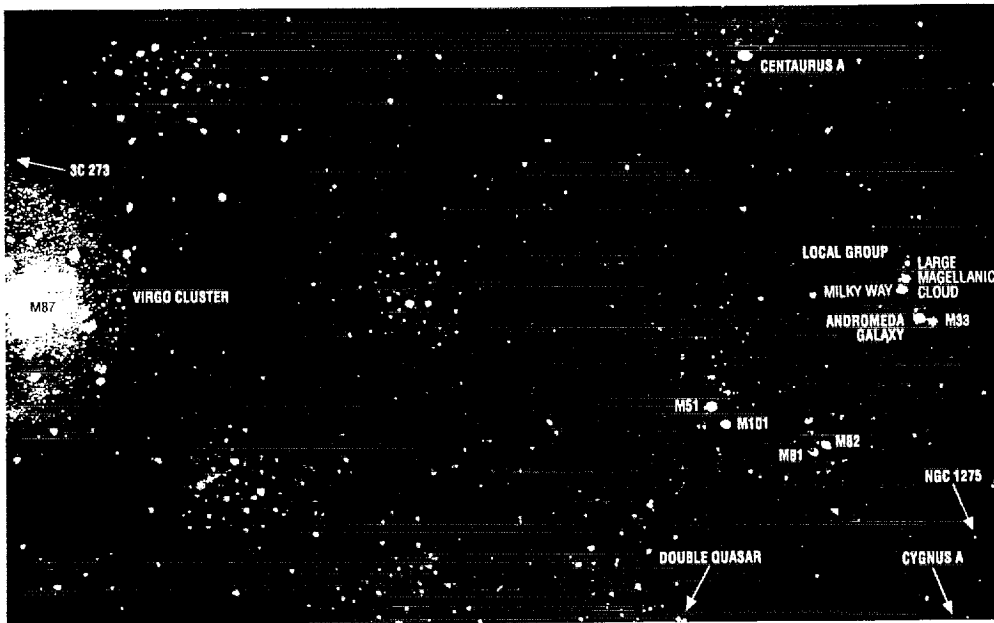


(Niels Bohr Library, American Institute of Physics)

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Edwin P. Hubble at the 48-in Schmidt telescope at Palomar Observatory
(Niels Bohr Library, American Institute of Physics)





Better "roadmaps" are needed for accurate distance measurements to galaxies much farther away than these neighboring galaxies.

How do we measure the universe?

When the United States decided to send men to the moon, scientists and engineers lacked an essential bit of information: the exact distance to the destination. At that time, no one knew precisely enough for navigation

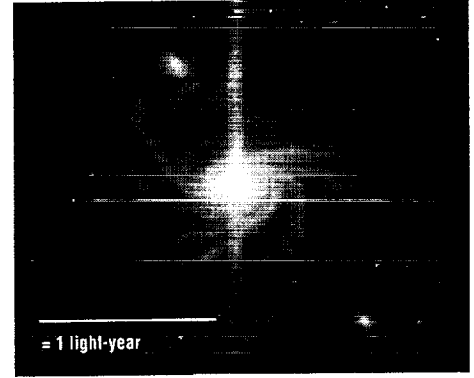
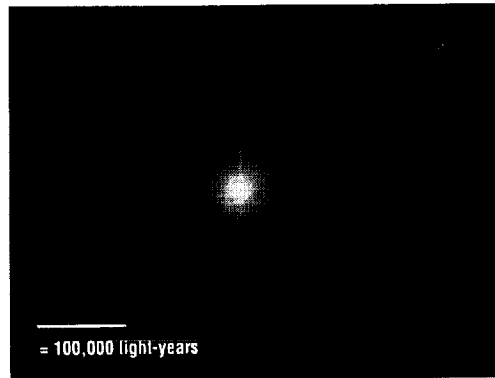
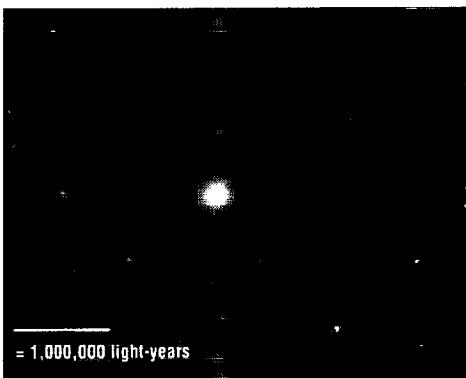
purposes just how far away the nearest celestial body was located.

Although the distances to some stars and galaxies are published as so many light years, these measurements in the celestial atlas are, in reality, estimates. The actual dis-

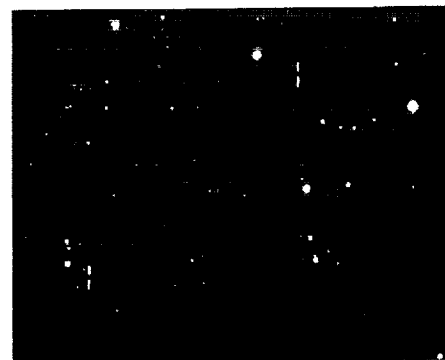
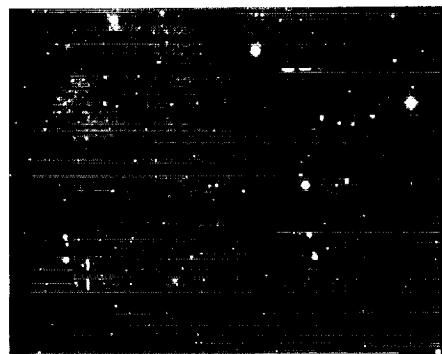
tance scale beyond the Milky Way has never been precisely determined; current estimates are so uncertain that galaxies may be twice as far away as we think, or only half as far.

Distance is crucial to almost every problem in astronomy, especially issues in cosmology about the origin and age of the universe. Astronomers need to know how far away the various bright and dim objects are and how far apart they are. A precise measurement of distance is also the basis for establishing an accurate value of the Hubble constant, a measure of the age and rate of expansion of the universe.

A high-priority project is to use the Hubble Space Telescope to refine the distance scale of the universe and to calculate a more accurate value of the Hubble constant. With its ability



The Hubble Space Telescope will resolve some of the detail that is usually lost over vast distances. (Adolph Schaller, artist)



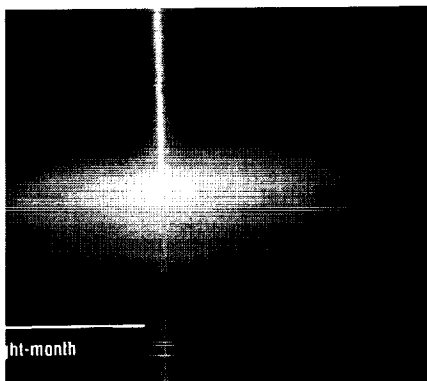
Cepheid variables are common reference points for astronomical measurements. The difference in brightness of these Cepheids in the Andromeda galaxy (between the dashed lines) is evident.

(Palomar Observatory, California Institute of Technology)

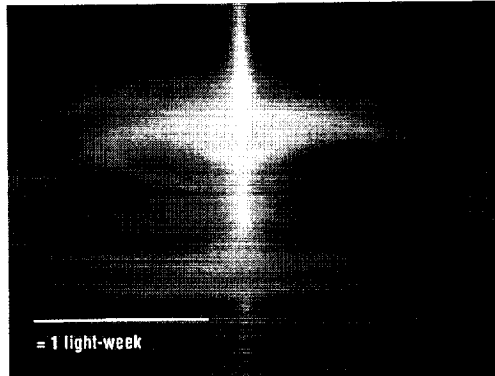


More accurate measurements of distances to objects in the Virgo cluster of galaxies, 60 million light years from our galaxy, will give scientists better "yardsticks" for calculating precise distances to objects much farther away.

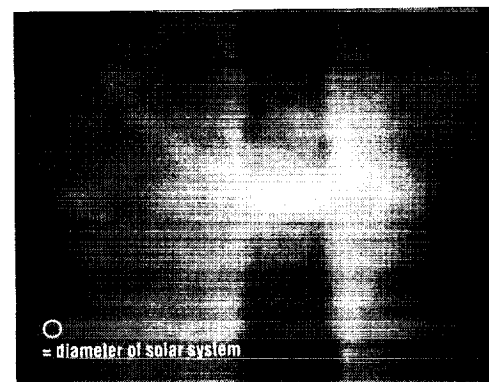
(Kitt Peak National Observatory)



light-month



= 1 light-week



○
= diameter of solar system

to measure very small angular shifts in the positions of stars, the telescope will survey the distance to a special class of stars known as Cepheid variables.

Cepheids are stars that brighten and dim on a regular schedule; they are used as "standard candles" because their intensities correlate with their periods of variation. These sources of known intensity provide a "yardstick" with which to measure distance. The apparent faintness of a Cepheid translates directly into its distance.

However, partial obscuration of the light by intervening dust and gas complicates the issue. We can now make accurate distance measurements only to nearby Cepheids — a few tens of millions of light years away. If we can measure the distance to galaxies out to the Virgo cluster, about 60 million light years away, then we can use this longer yardstick to determine more accurate distances to other objects farther away.

By analogy, if at home we

did not have a ruler or measuring tape, we might use a piece of string for successive measurements until we could say that the room was so many lengths of string wide by so many lengths of string long; that unit of measure could be used as a "yardstick" for gauging the distances to other objects. The Cepheid project will take several years to complete, since measurements must be repeated and compared at regular intervals to refine the distance calculations.

**What are quasars,
active galaxies, and
other exotic objects?**

Among the most mystifying celestial bodies are quasars, active galaxies, neutron stars, and other compact objects that appear unusually luminous for their size. Because these objects are relatively small and very far away, we have not been able to

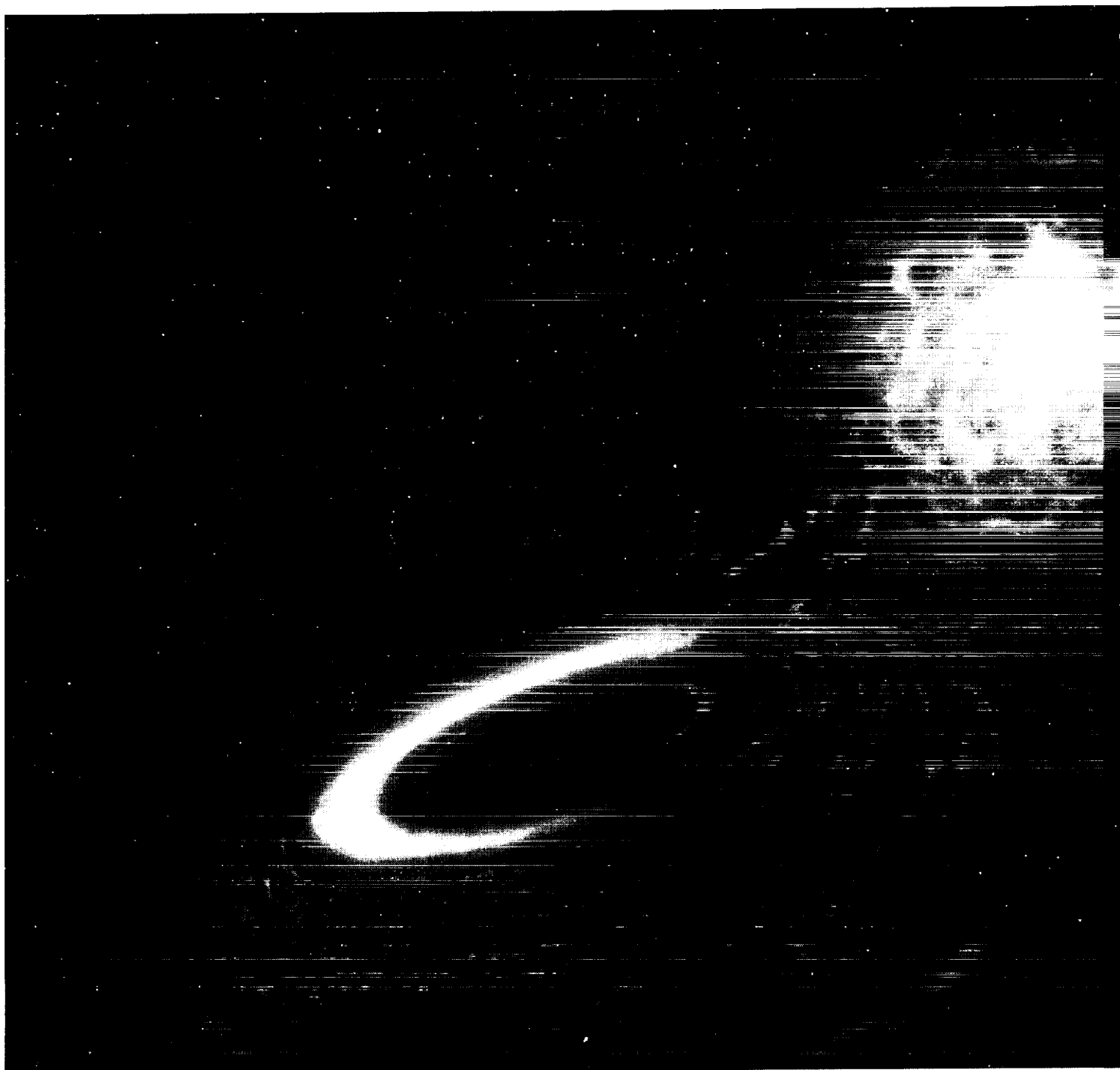
determine exactly what they are. With the Hubble Space Telescope, however, the nature of these enigmas should be revealed.

Quasars are especially puzzling. The most distant observable objects, they should be very faint; however, a quasar the size of a solar system can produce hundreds of times as

much radiation as an entire galaxy. Interestingly, a quasar may be hardly noticeable in visible light, but it blazes forth in higher-energy radiation (ultraviolet and X-rays). The brightness of some quasars varies from month to month, even from one hour to the next. There is no explanation for the source of this immense energy or its vari-

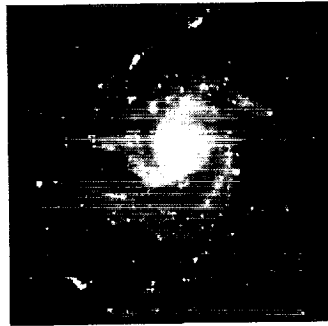
ability. Are quasars powered by black holes or by something yet to be discovered? The quasar problem challenges our current understanding of the laws of physics.

The most distant quasars, as far away as 15 billion light years, are thought to be at the limits of the observable universe. Because looking far out

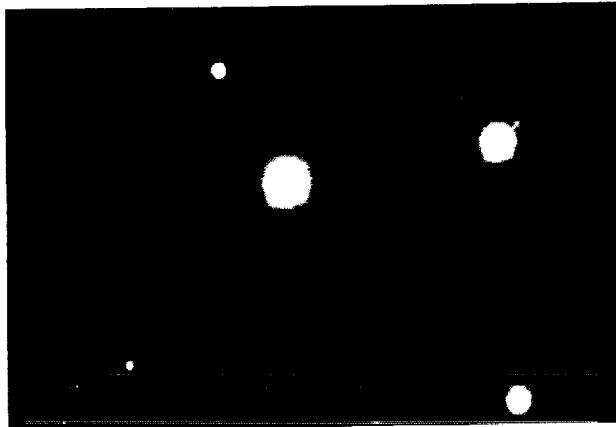


nto space is looking back in
ime, we see quasars today as
hey appeared billions of years
ago; they may not even exist
ow. Quasars may be explo-
sions that precipitate galaxies,
he violent first step in an evolu-
tionary process that gradually
results in a normal galaxy like
our own.

In some galaxies, the central
region emits extraordinarily
intense and variable radiation.
It is thought that quasars or
black holes hidden in these
active galaxies may be the
power source. High-resolution
studies of the centers of galaxies
by the Hubble Space Telescope
should reveal this mysterious
phenomenon.



Observations in different radiation bands reveal different features, as shown in these two images of the M101 galaxy, one in visible light (left) and the other in ultraviolet (right). Only the higher-temperature objects and areas appear in ultraviolet images, while the cooler ones disappear. (Kitt Peak National Observatory, visible; NASA Goddard Space Flight Center, ultraviolet)



Quasar 3C 273 in Virgo is a mysterious object that may radiate 100 times more light than the brightest ordinary galaxy.

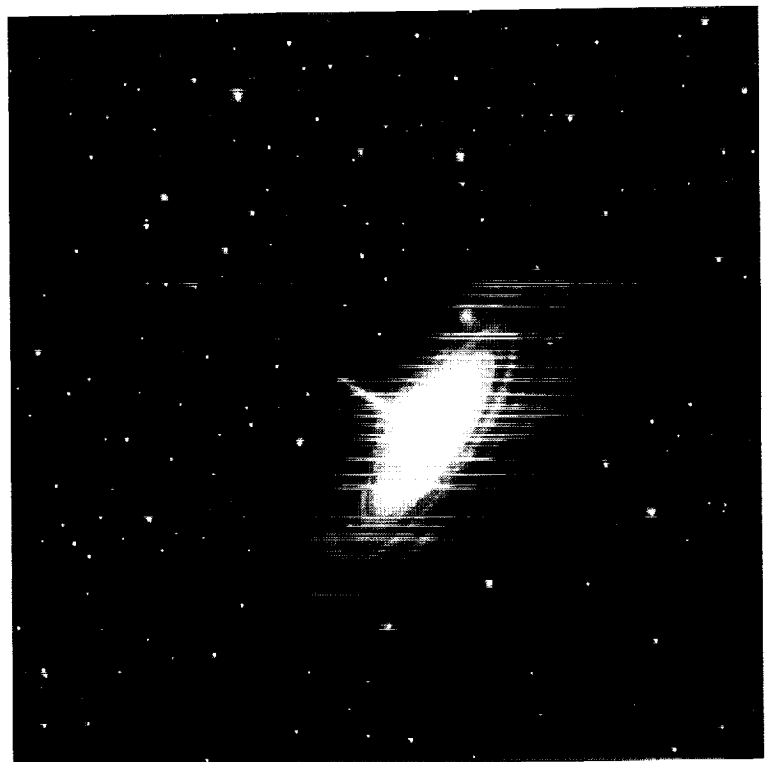
(Kitt Peak National Observatory)

Some quasars and other objects emit perplexing jets of radiation.

(Adolph Schaller, artist)

The existence of black holes, which may devour matter from nearby stars, is theorized but not yet confirmed.

(Don Dixon, artist)



How do galaxies form and evolve?

There are an estimated 100 billion galaxies in the universe, and we know only one reasonably well: our own Milky Way. As recently as the 1920's, when Edwin P. Hubble corrected the record, no one knew with certainty that other galaxies existed. Since then, galaxies have been identified, labeled, and placed in a classification scheme based on their structure or other features, but only a fraction of the total population of galaxies has been sampled.

Galaxies are intrinsically interesting evidence of the origin of the universe, for it is thought that they were the first objects to form after the cosmic "Big Bang." They seem to be the basic building blocks that give structure to the universe. Curiously, there is little evidence that new galaxies are forming today.

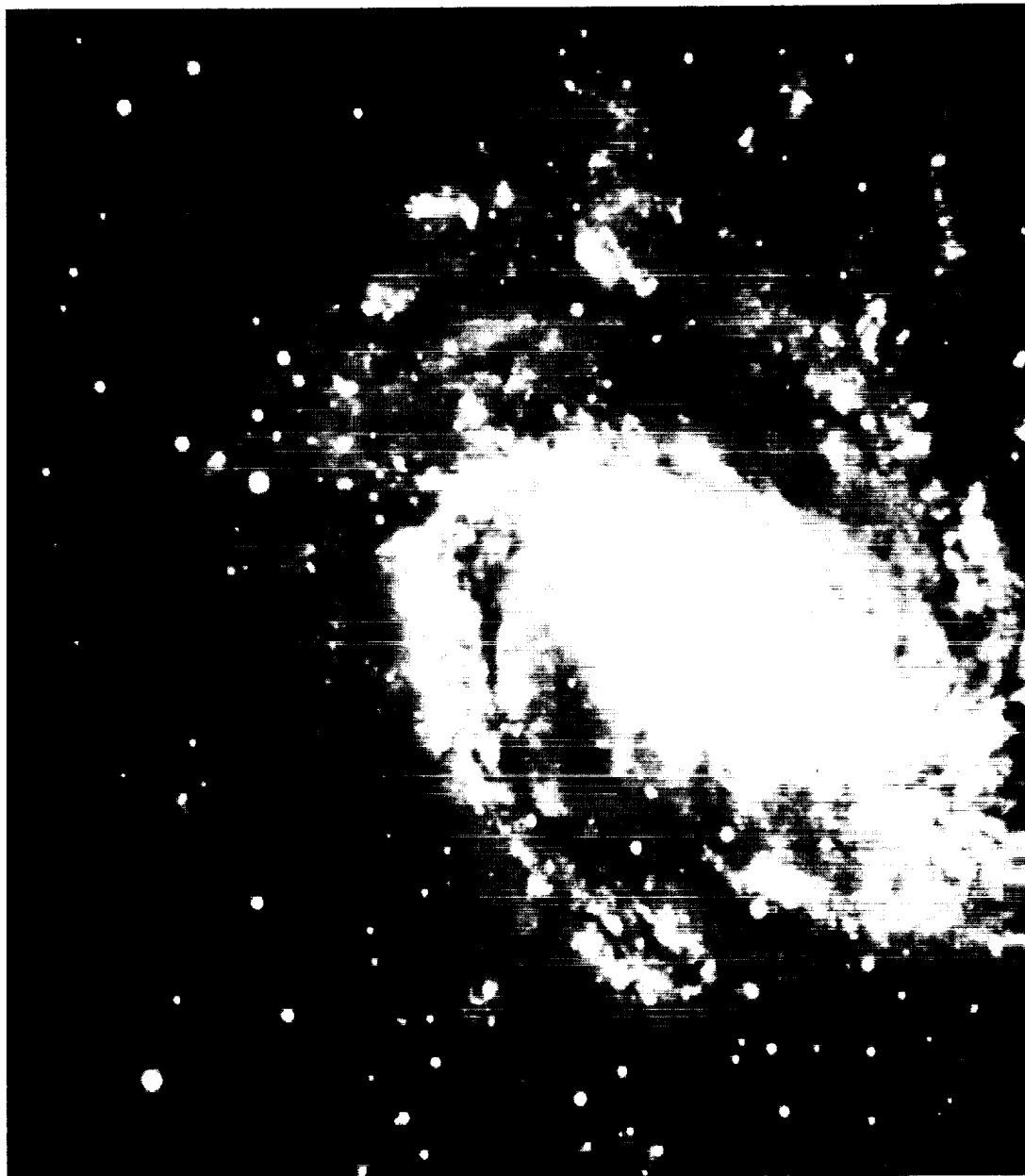
Astronomers are eager to see the farthest (youngest) galaxies out toward 15 billion light years, for these should reveal the conditions under which the universe began to take shape. To understand how the universe evolved, astronomers need to study as many galaxies of as many types and ages as possible. Today, only the 20 nearest galaxies have been studied in any detail; these are contemporaries of the Milky Way, similar in form and content. A more thorough census is required.

With the very sensitive Hubble Space Telescope, astronomers will be collecting information about galaxies

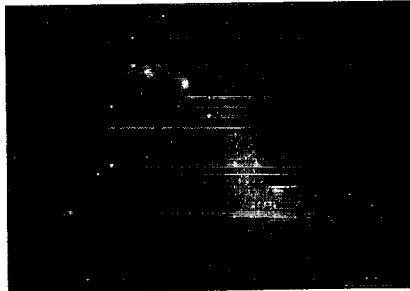
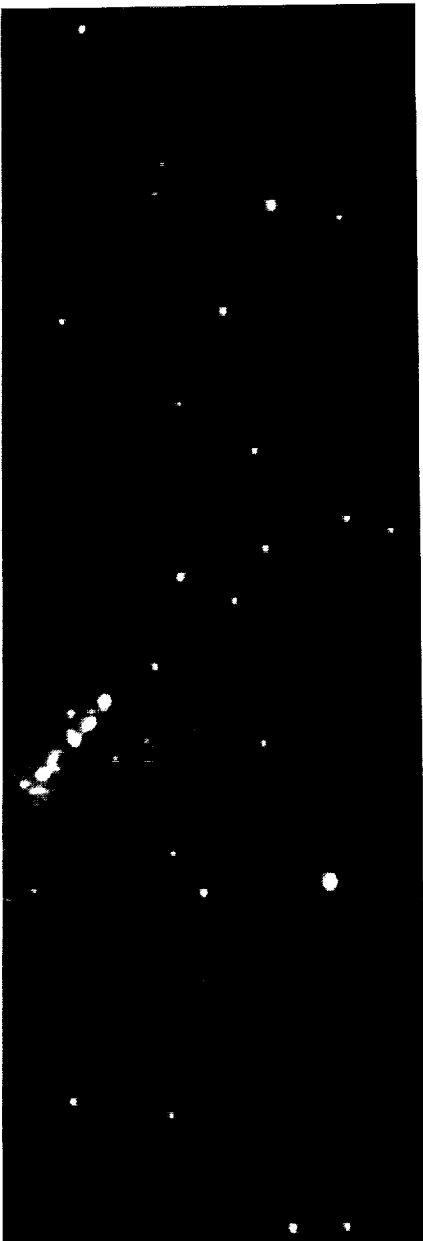
during the early stages of their formation and adding new galaxies to the list of those available for study. In addition, they will get a more detailed look at some puzzling phenomena, such as active galaxies that produce extraordinary energy compared to typical galaxies. It is thought that the nuclei of such galaxies may harbor quasars or black holes, which are not yet well understood. With the improved resolution of this telescope, astronomers will be able to peer into the crowded centers of galaxies to find what lies hidden there.



Celestial merger: galaxies may collide and interact, exchanging matter and resulting in the formation of new stars. (Brian Sullivan, artist)



Spiral galaxy M83 in Hydra
(Cerro Tololo Inter American Observatory)

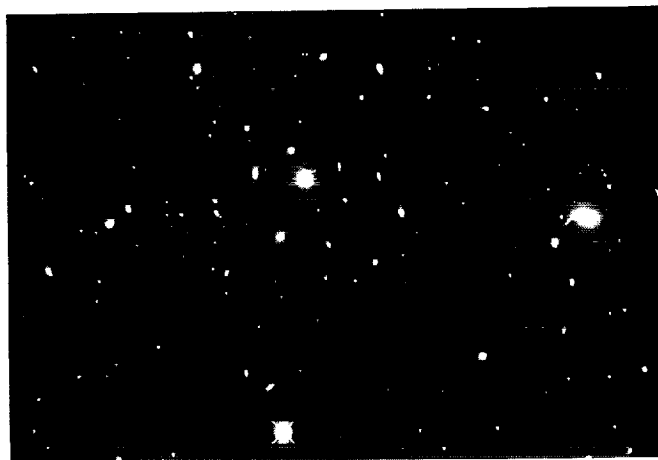


The Hubble Space Telescope will be used to observe a variety of galaxies of different types, distances, and ages:

Small Magellanic Cloud
(Royal Observatory)



Whirlpool Galaxy in Canes Venatici
(Palomar Observatory, California Institute of Technology)



Cluster of galaxies in Coma Berenices
(Kitt Peak National Observatory)

What is the life cycle of stars?

Stars are forming in our galaxy and elsewhere today. Although the Milky Way is more than 10 billion years old, we see stars that are thousands of times younger. Occasionally, we also see stars in the death process, exploding as supernovas and disappearing or shrinking into white dwarfs.

The rationale for observing stars is much the same as that for observing galaxies; scientists need to study many stars of many different ages and types to understand how they form, exist, and die. Stellar population studies are an important item on the agenda of the Hubble Space Telescope. Thousands of stars will be measured and categorized to obtain a large statistical sample.

Studying other stars tells us more about the nearest star, our sun, which formed relatively late in the galaxy's life. Although the Hubble Space Telescope cannot look at the sun, the

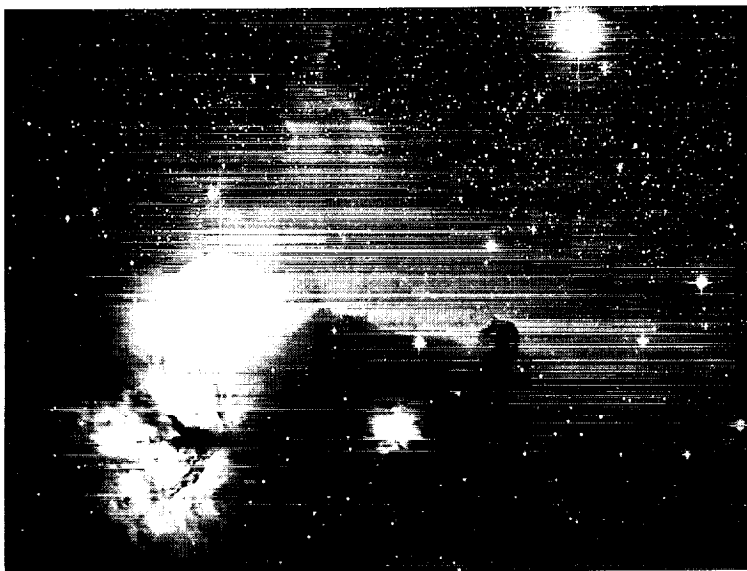
broad stellar survey will help us understand the processes that govern it. Detection of proto-stars (clouds of matter that are condensing into stars) and stars that form earlier in the history of a galaxy may give insight into the formation and early history of our solar system.

Many faint stars will appear as bright sources to the highly sensitive instruments in the Hubble Space Telescope. The standard deep sky atlas, the Palomar Observatory Sky Survey, includes stars as faint as 21st magnitude. While the Hubble Space Telescope will not be used for a full-sky survey, it will be able to detect stars to at least the 28th magnitude and easily record 24th magnitude stars, which are the faintest routinely observable from ground observatories. It will also be able to record faint starlight much more quickly than long overnight exposures from the ground. Hubble Space Telescope exposures will range from tenths of a second to about an hour.



Nebulae are often called stellar nurseries, because new stars form in these glowing clouds of dust and gas.

(Trifid Nebula in Sagittarius, Kitt Peak National Observatory)

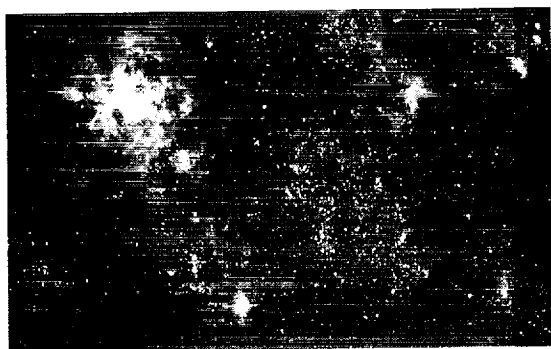


Horsehead Nebula in Orion is an opaque cloud of dust that absorbs light from stars beyond it. *(Royal Observatory)*

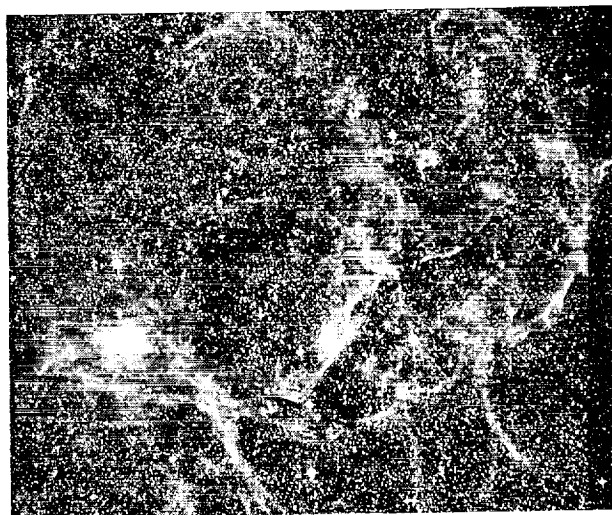
The Pleiades are a cluster of about 3,000 stars in Taurus; the Hubble Space Telescope will be able to resolve stars in more distant and very dense clusters.

(Hansen Planetarium)





A supernova is a stellar explosion that temporarily may outshine all other stars in its galaxy. An interesting target of observation is the supernova discovered in 1987 in the nearby Large Magellanic Cloud.
(European Southern Observatory)



Supernova remnants, hollow shells of gas, may linger for centuries as glowing evidence of the death of a star.
(Supernova remnant in Vela, Royal Observatory)

Do other planetary systems exist?

Given the tremendous number of stars in the universe, it is unlikely that our solar system is the only collection of planetary bodies. Theoretically, the formation of planets about a star could be a normal process. The search for other planetary systems is pertinent to understanding the evolution of the universe, and it is an exciting scientific adventure.

The Hubble Space Telescope is not likely to observe planets around another star directly, for they would be extremely faint, obscured by the star's bright light. However, it may be possible to find secondary evidence of a planet from wobbles in the star's motion that indicate the gravitational pull of an orbiting body. Similarly, fluctuations in a young star's light output might suggest a rotating, dusty disk where a new planetary system could be forming. If companions are suspected around a candidate star, it is possible to create within the telescope an artificial eclipse of the star's light so a smaller, dimmer body may be detected. Highly precise position measurements with the Hubble Space Telescope could then reveal whether or not the newly visible body were orbiting the central star.

Another exciting use of the Hubble Space Telescope is to focus on the planets and moons in our own solar system, giving us a front row view of these fascinating worlds almost

comparable to photos from the Voyager spacecraft. Whereas the exploratory Voyagers had only a fleeting glance at Jupiter, Saturn, Uranus, and Neptune, the Hubble telescope can study them whenever we desire, repeatedly and in finer detail than observations from the ground. Thus, the telescope complements the discovery missions by providing for longer-term study. For example, while Voyager first showed us evidence of volcanoes on Jupiter's moon Io, the Hubble Space Telescope will tell us how often they erupt and what chemicals they emit. One of the cameras in the Hubble observatory can photograph the entire Earth-facing hemisphere of any planet in our solar system (except Mercury, which is too close to the sun) in a single exposure; it is possible that our first "close up" look at Pluto will be among the images received when observatory operations begin.

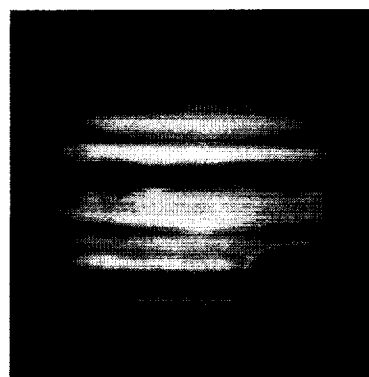
Comets are important targets of observation, because they are thought to be debris from the formation of the solar system, frozen and essentially unchanged for four billion years. Comets may tell us what chemicals, in what abundance, were present when our solar system formed. The Hubble Space Telescope is useful for cometary science, because it can examine a comet at many points along its trajectory through the solar system. Thus, astronomers need not wait for the next close approach to Earth to collect comet data. ☿

The Hubble Space Telescope will enable studies of the planets in finer detail than is possible from the ground.

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A close-up view of Jupiter and its moons Io (left) and Europa (right) comparable in detail to expected Hubble Space Telescope images. This image was obtained at a distance of 20 million km (12.4 million mi) by the Voyager spacecraft. (NASA)

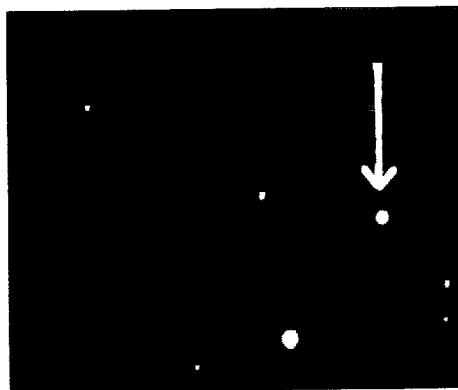


One of the best images of Jupiter from a telescope on the ground (Palomar Observatory, California Institute of Technology)

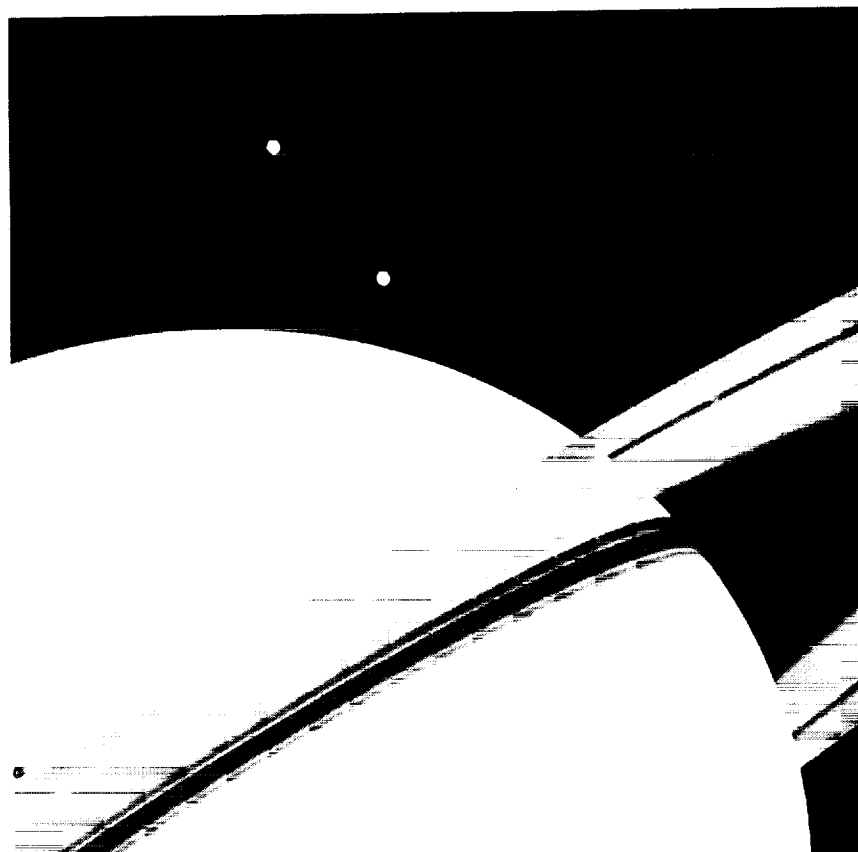
The Hubble Space Telescope will give us a front row view of the fascinating worlds of our solar system.



A large, bright, circular light source, possibly a sun or moon, centered in a dark, textured field. The light source has a soft, glowing edge and a slightly grainy texture, suggesting it might be a photograph of a celestial body. The surrounding field is dark and has a fine, stippled texture, giving it a sense of depth and atmosphere.



**A Voyager image
of Saturn from
13 million km
(8 million mi),
comparable in
resolution to
Hubble Space
Telescope imagery**
(NASA)



Using the **Hubble Space Telescope**

Like polished sterling, the Hubble Space Telescope gleams against the velvet drape of night. Its design is sleek: a long case, covered with sun-foil, not unlike an amateur telescope or kaleidoscope in its simple contour, though much larger. The distinctive features marking it as a spacecraft are two solar panels and two fragile antennas. It could be a modern sculpture, a silvery winged creature embarking on a flight into the cosmos.

Orbiting some 370 miles above us, this telescope is an extremely sensitive light catcher, ready for the arrival of infinitesimal bits of visible, infrared, and ultraviolet energy that have traveled billions of years through space. The light detected today originated so long ago and so far away that its arrival is greeted with curious anticipation. This welcome messenger can reveal to us what the universe is like, how it began, and how it changes.

The jewel of the telescope, the 8-foot primary mirror, is deep inside the protective case. The mirror is a marvel of technology: large but lightweight, its pure aluminum reflecting surface thinly coated with transparent magnesium fluoride. To focus faint light as precisely as required, the mirror had to be virtually perfect, and it is. No bump or ripple on its polished surface deviates more than one millionth of an inch from an ideally perfect curve; no mirror has ever been more finely polished or more evenly coated. If the Earth were as smooth, the highest peak and the deepest valley would vary from the surface by less than three inches.





***The Hubble Space Telescope:
The greatest advance in
astronomy since Galileo***

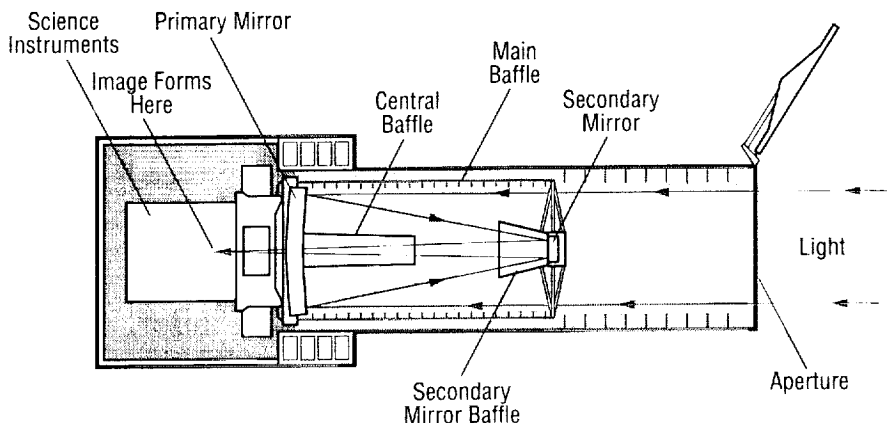
The Hubble Space Telescope is an observatory unlike any astronomical observatory on Earth.

Light entering the telescope strikes the primary mirror, is reflected forward to the secondary mirror where it is reflected again, returning down the telescope and through a hole in the primary mirror to the focal plane, where the image forms. There, detectors record images or analyze the incoming ultraviolet, visible, or infrared light. These focal plane instruments are crucial to the observatory; without them, the advantage of the perfect mirror and vantage point above the atmosphere would be wasted. The detected light is converted into electronic signals and transmitted by relay satellite to ground stations. There the data are processed by computers and reconstructed as images for astronomers to study.

The Hubble Space Telescope is an observatory unlike any astronomical observatory on Earth. Some of the differences are obvious. It doesn't have the

familiar dome shape of observatory buildings, because it needs no protection against weather. It has peculiar features like solar panels, to generate electrical power, and communications antennas, to receive and transmit information. The telescope is remotely controlled by operators hundreds of miles below it and, at times, half a world away. It operates around the clock, day and night, seven days a week, year after year, unaffected by clouds and weather. Visibility is always perfect.

More subtly, the Hubble Space Telescope represents a revolutionary shift in the way most astronomers do their work. During the deployment, operational, and servicing phases of its mission, the telescope is handled differently than is customary for a ground-based telescope. With the Hubble Space Telescope, astronomical research reaches maturity in the space age.



Path of light through the telescope to the detectors



***Control room in the Space
Telescope Operations Control
Center at NASA's Goddard Space
Flight Center in Maryland***
(NASA)

***The Hubble Space Telescope
will be delivered to orbit
by the Space Shuttle.
Initial checkout will occur
while the telescope is
attached to the Shuttle; then
it will be released for years
of operation in space.***

(Gordon Raney, artist; Lockheed)

Observing with the Hubble Space Telescope

In the nearby media center, journalists keep vigil, their editors and producers saving front pages and prime time for on-the-scene reports. Across the country at NASA centers and aerospace firms, thousands of people involved in the project know that today is the red letter day, the culmination of years of effort. Around the world, astronomers await word that the new observatory is deployed, promising new vistas for the most ancient science.

Actually, ground controllers have been "talking" to the telescope since four hours after launch, waking the various systems and readying them to be turned on. For launch, the

telescope is dormant; its activation in orbit is a methodical procedure that lasts about three days for initial deployment and several months for full checkout. This verification sequence carefully brings the telescope to full operational status.

About 24 hours after launch, the telescope is unplugged from the Shuttle power supply and begins operating on its own battery power. It is then lifted from the bay by the robot arm and held outside the Shuttle during preparations for release. The solar arrays must be deployed promptly to activate the telescope's internal power system, and the antennas must be unstowed for two-way

command and data flow. By the second day in orbit, the telescope is ready to be released.

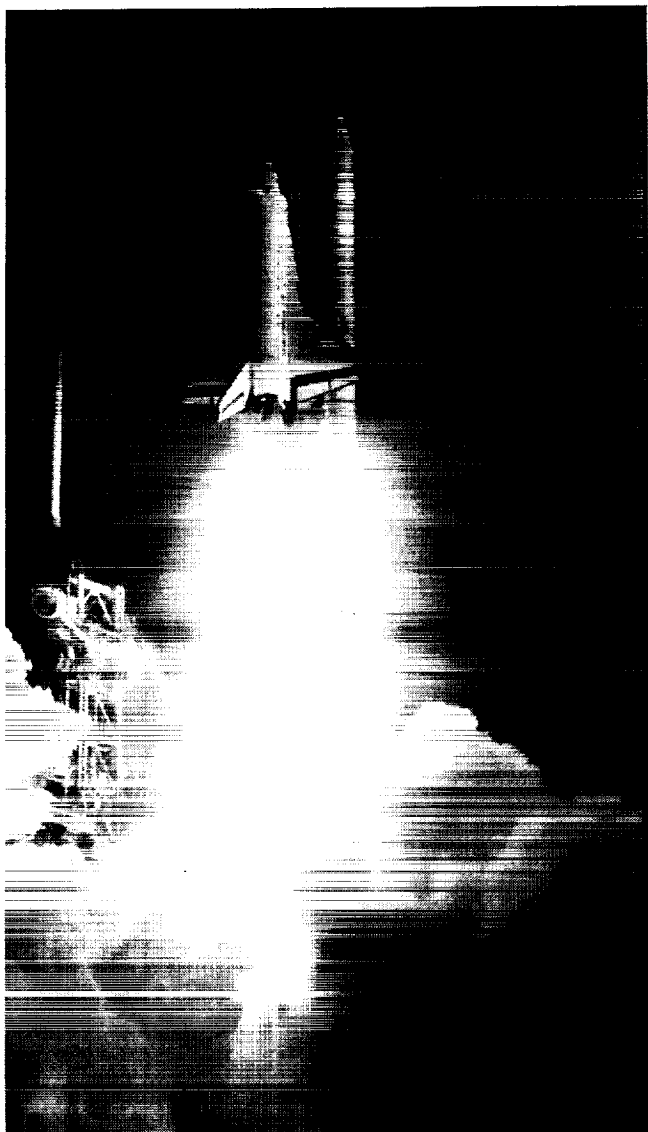
For the next several hours, the ground control teams put the telescope through its paces, gradually bringing it up to full power, turning on its "house-keeping" systems for pointing and attitude control, loading the computer memories, and testing the telemetry. These activities verify that everything is working properly as the telescope adjusts to the space environment.

The third and fourth days are dedicated to testing the telescope's ability to move and point accurately, to acquire guide stars and targets. Then the alignments of the mirrors and scientific

instruments are checked, and calibration tests are run. About two weeks into the mission, checkout of the cameras and other scientific instruments in the focal plane begins.

Checkout is a time for patience. A full six months have been allocated for meticulous verification that all systems and instruments are functioning properly. This period will be punctuated by some actual observations, but the observatory's schedule will not be turned over to the scientists until the checkout is complete.

Two NASA centers share responsibility during this trial period. The Marshall Space Flight Center in Huntsville,



Astronauts working in the aft flight deck of the Space Shuttle deploy the Hubble Space Telescope.

(NASA)

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Space Telescope in Orbit

First Days

Slowly and gently, the telescope is lifted from its cradle in the payload bay of the Space Shuttle. Attached to the spidery remote manipulator arm, the 43-foot telescope clears the bay door and is held overboard for a methodical checkout before release. There is no ribbon-cutting ceremony, no cornerstone to set in place, no speech under

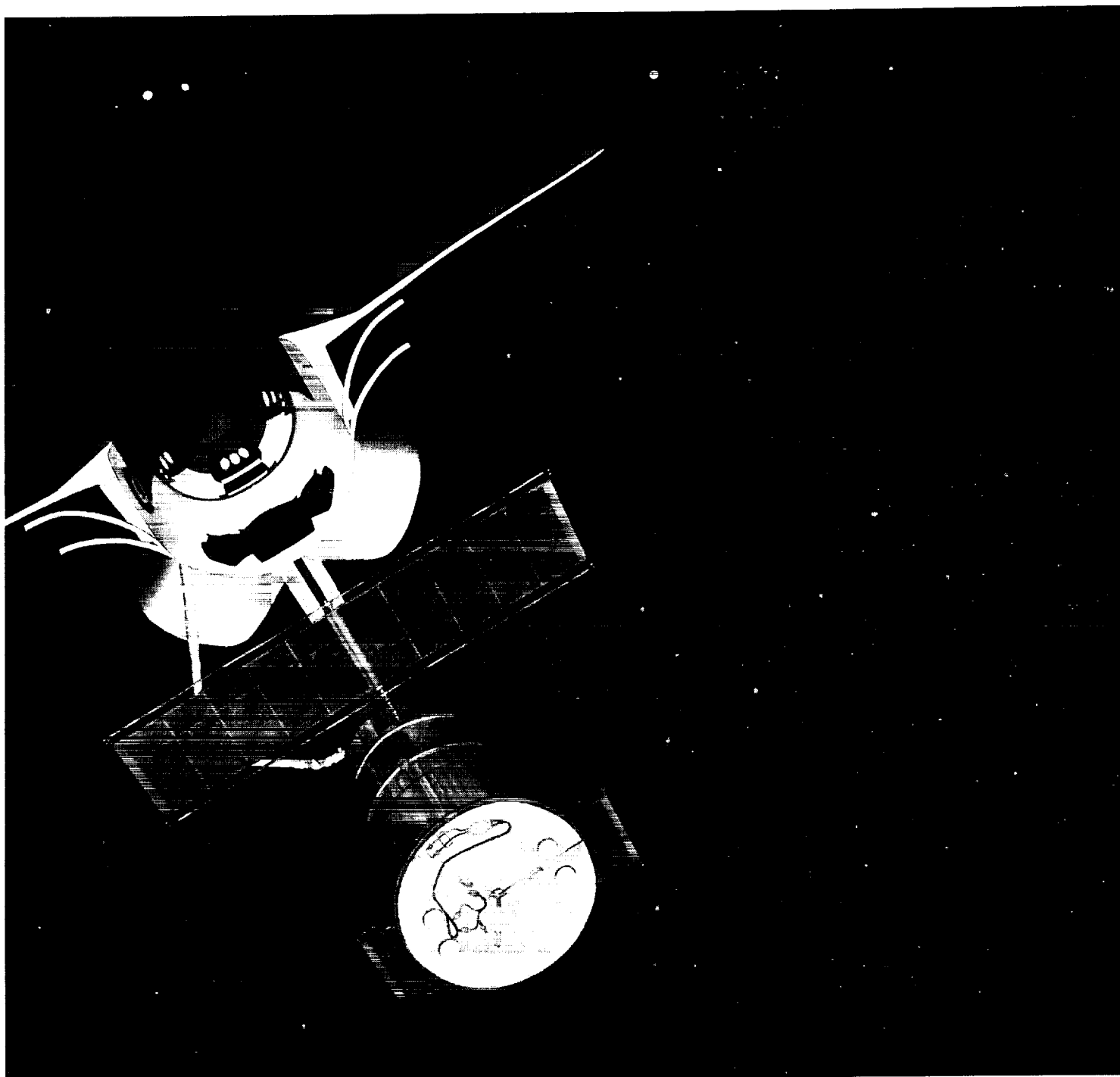
a dome. Instead, opening night activities proceed in a brisk, businesslike fashion. Only five people are present.

Inside the Shuttle, an astronaut intently watches through a window and operates the mechanical arm to position the telescope for the first stages of its deployment. The commander is on duty to oversee activity, while the pilot maneuvers the

Shuttle. Two other crew members stand by, prepared to go to work outside the cabin if some problem arises.

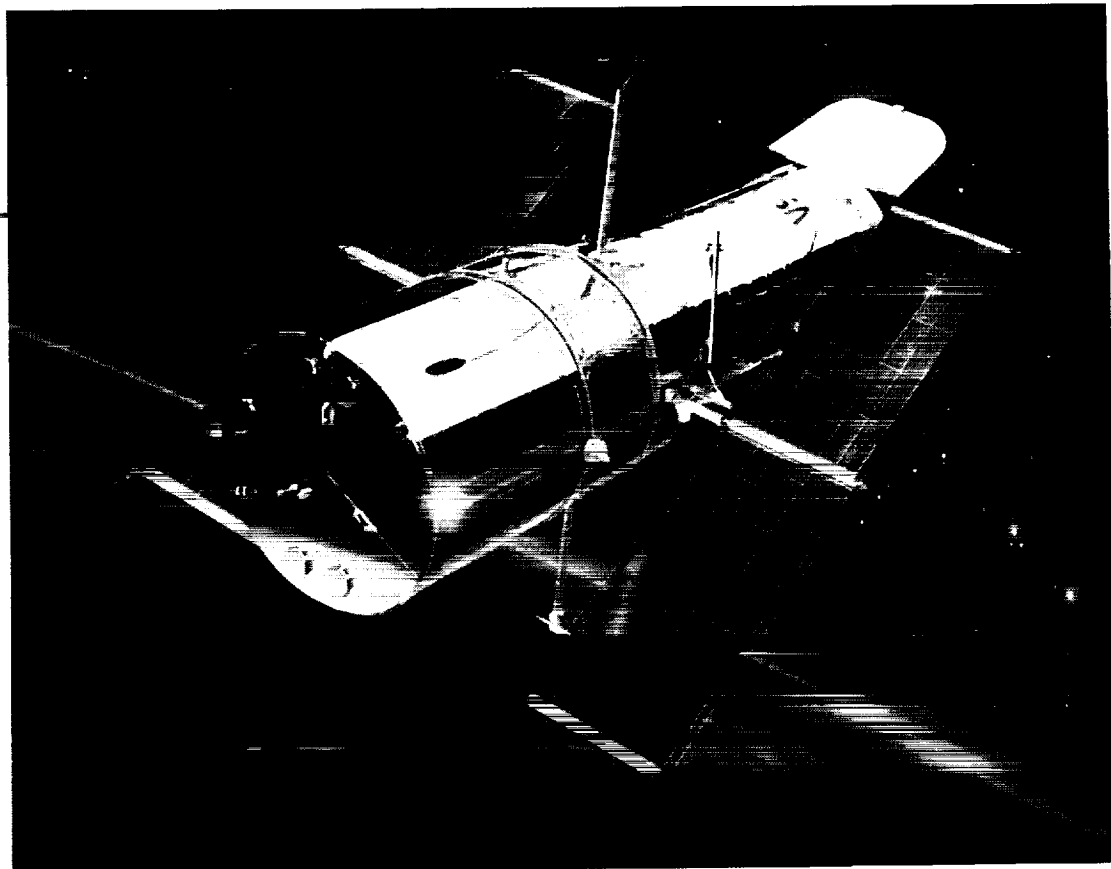
Meanwhile, scores of personnel at ground control centers monitor every electronic signal and issue commands as the telescope is being prepared to operate in space. The mood is vibrant; scientists, engineers, managers, and VIPs concentrate

on video screens and adjust their headsets, listening quietly to terse status reports. "Solar arrays deployed...power-up sequence initiated..." The two solar arrays gradually unfurl, and then the two antennas fold out. The Shuttle eases away to a respectful distance, where it hovers until the initial checkout is complete.



Alabama, NASA's lead center for development of the Hubble Space Telescope, will conduct the general spacecraft systems checkout. The Goddard Space Flight Center in Greenbelt, Maryland, is responsible for verifying the performance of the scientific instruments. Activation and checkout will be conducted from the Space Telescope Operations Control Center at Goddard. Engineering teams in the Huntsville Operations Support Center and at sites of the various contractors responsible for constructing the telescope will support these activities. After the general systems checkout, operational and managerial control of the Hubble Space Telescope will pass from Marshall to Goddard, which will then be the focal point of day-to-day operations such as telescope pointing, instrument commanding, and data flow.

As in all Space Shuttle missions, the Kennedy Space Center at Cape Canaveral, Florida, and the Johnson Space Center in Houston, Texas, serve as control centers for the launch and manned spaceflight phases of the Hubble Space Telescope's deployment and subsequent servicing missions.



Hubble Space Telescope in orbit
(Lockheed)

The first several months in orbit are reserved for checkout and verification of the telescope before science operations begin.

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ORBIT #		016	163E ▼	017	139E ▼	018	114E ▼	019	109DE ▼	020
LIGHT/SHADOW										
SAA										
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ORBITER		◀ ORBITER INERTIAL	ORBITER FREEDRIFT DURING PDM, SDM DEPLOY			ORBITER INERTIAL		ORBITER SEPARATION		
CREW		RMS DEPLOY HST ▶	◀ CREW MONITOR, FILM SA DEPLOYMENT ▶			◀ CREW FILM SA ROTATE ▶	RMS POSITION HST FOR RELEASE	• RMS POSITION • HST FOR RELEASE		

Segment of the deployment mission timeline
(NASA)

Observing with the Hubble Space Telescope

Day-to-Day Operations

Several months after launch, when all checkout and verification exercises are completed, NASA officially hands over science planning responsibility for the Hubble Space Telescope to the Space Telescope Science Institute in Baltimore, Maryland. The Institute is responsible for the scientific use of the observatory, which will continue to be operated by the Goddard Space Flight Center. This dual control of the telescope's operation is a new arrangement that reflects

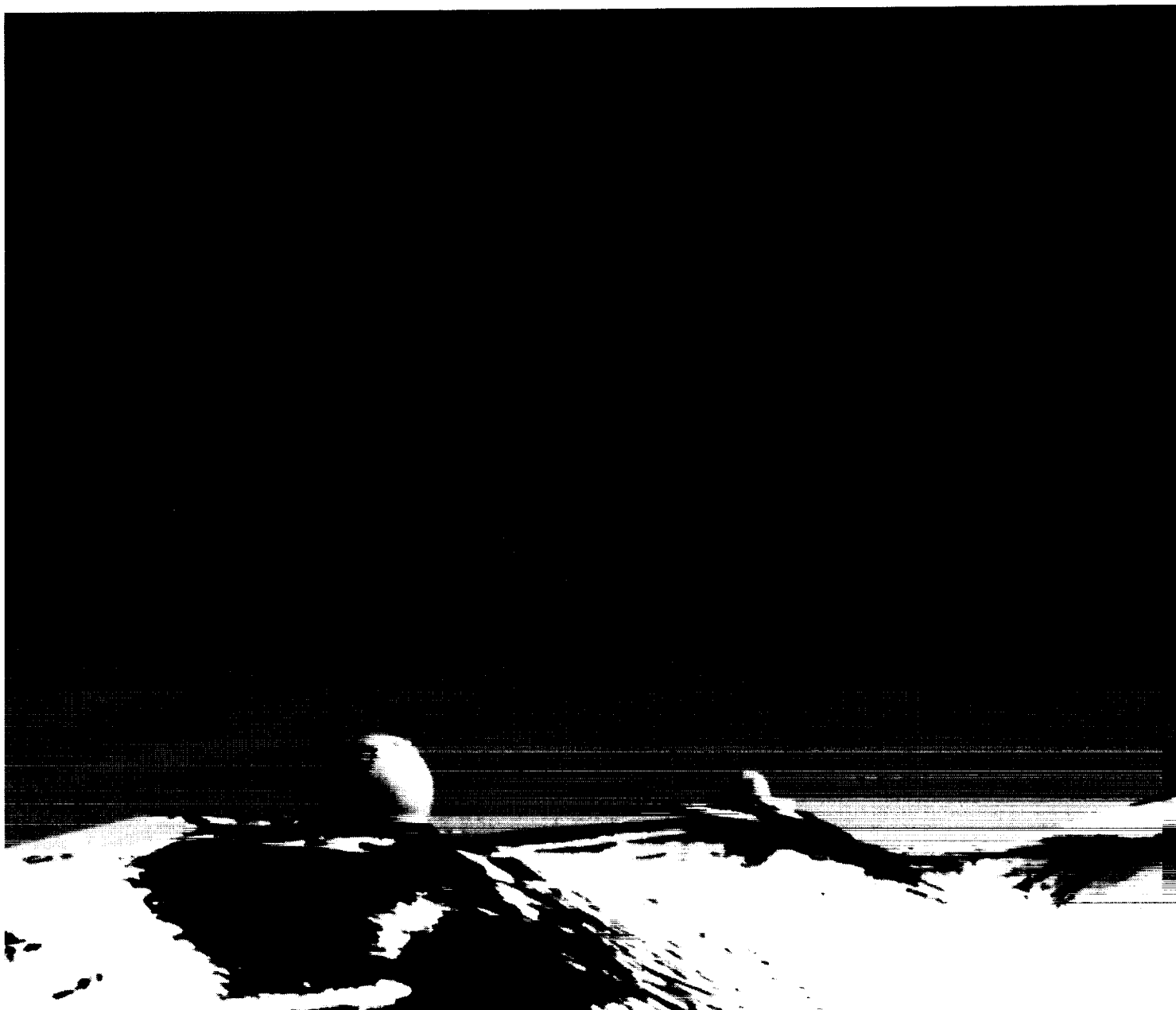
some of the basic differences in the ways astronomers use observatories on the ground and in space.

The Hubble Space Telescope is not the first telescope in space; a number of smaller instruments have flown since the 1960's. However, it is the first large orbital observatory to be accessible to the worldwide astronomical community and the first such telescope to be considered "permanent." Like Mount Palomar or other world-class observatories on the ground, the Space

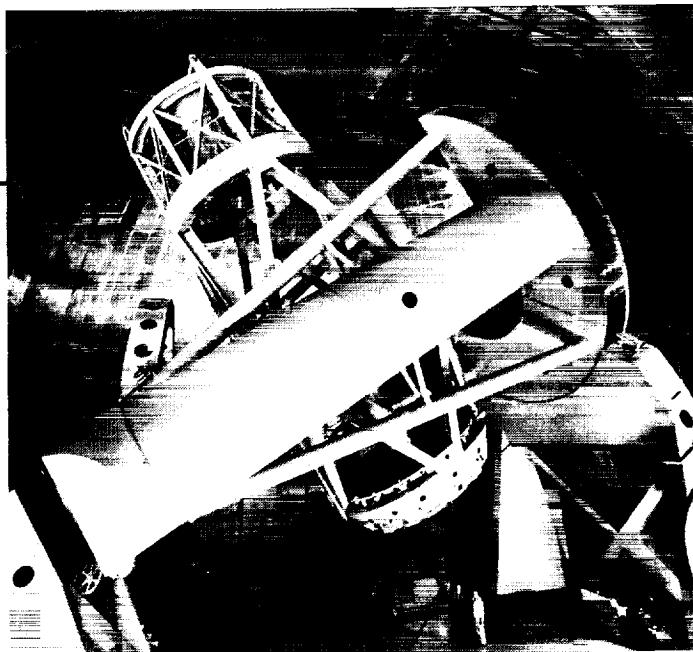
Telescope will host a changing program of investigations and guest observers while it is in service. What is it like to be an astronomer using the Hubble Space Telescope?

To work in some of the best observatories on Earth, an astronomer may fly halfway around the world and then travel many miles overland to reach a remote mountaintop for a few nights of observation. Normally, he or she books time at the observatory several months in advance, arrives on the sched-

uled date and takes up residence there, hopes for several nights of good visibility, and, if the weather isn't cloudy, proceeds to observe whatever targets are critical to his or her research. Usually no one else is scheduled to use the facility at the same time, so the astronomer works without interruption. The observatory staff assist in configuring the equipment, pointing the telescope, and supporting the guest observer's plan. The astronomer and observatory technicians may sit side



by side in the control room, choosing targets and adjusting the instruments through the night in response to observing conditions. The telescope is essentially an extension of the observer's senses, responding immediately to the astronomer's desire to linger on a particular target or look elsewhere. When astronomers go to bed at dawn, their work has only begun. The harvest of data from one night's observations may take months, even years, to analyze and understand.

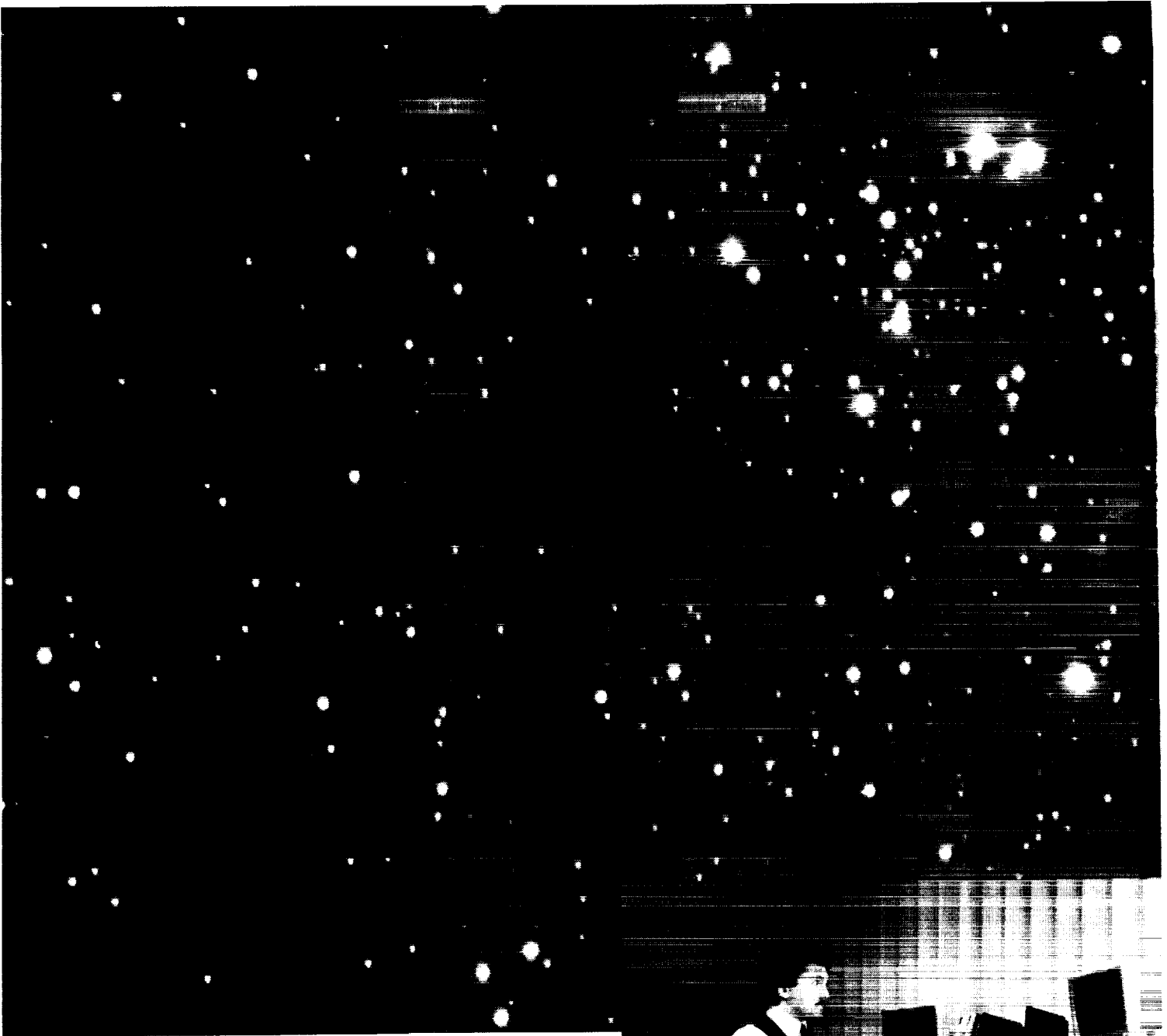


In observatories on the ground, astronomers work in a control room a few steps away from the telescope; however, the Hubble Space Telescope is a remotely controlled observatory.

(Hale Observatory)

Mountaintop observatories at Mauna Kea
(Canada-France-Hawaii Telescope Corporation)



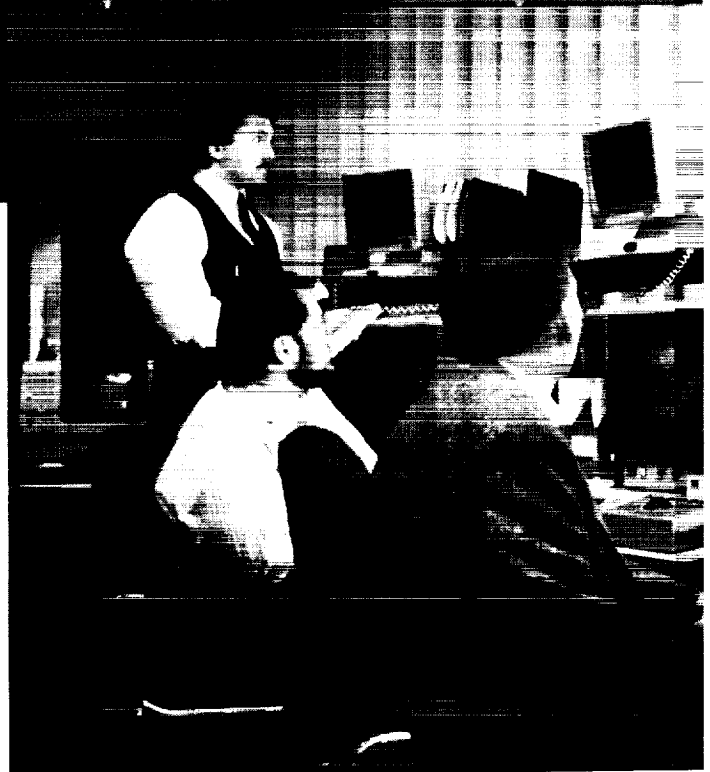


Gaseous Nebula in Serpens
(Hale Observatories)

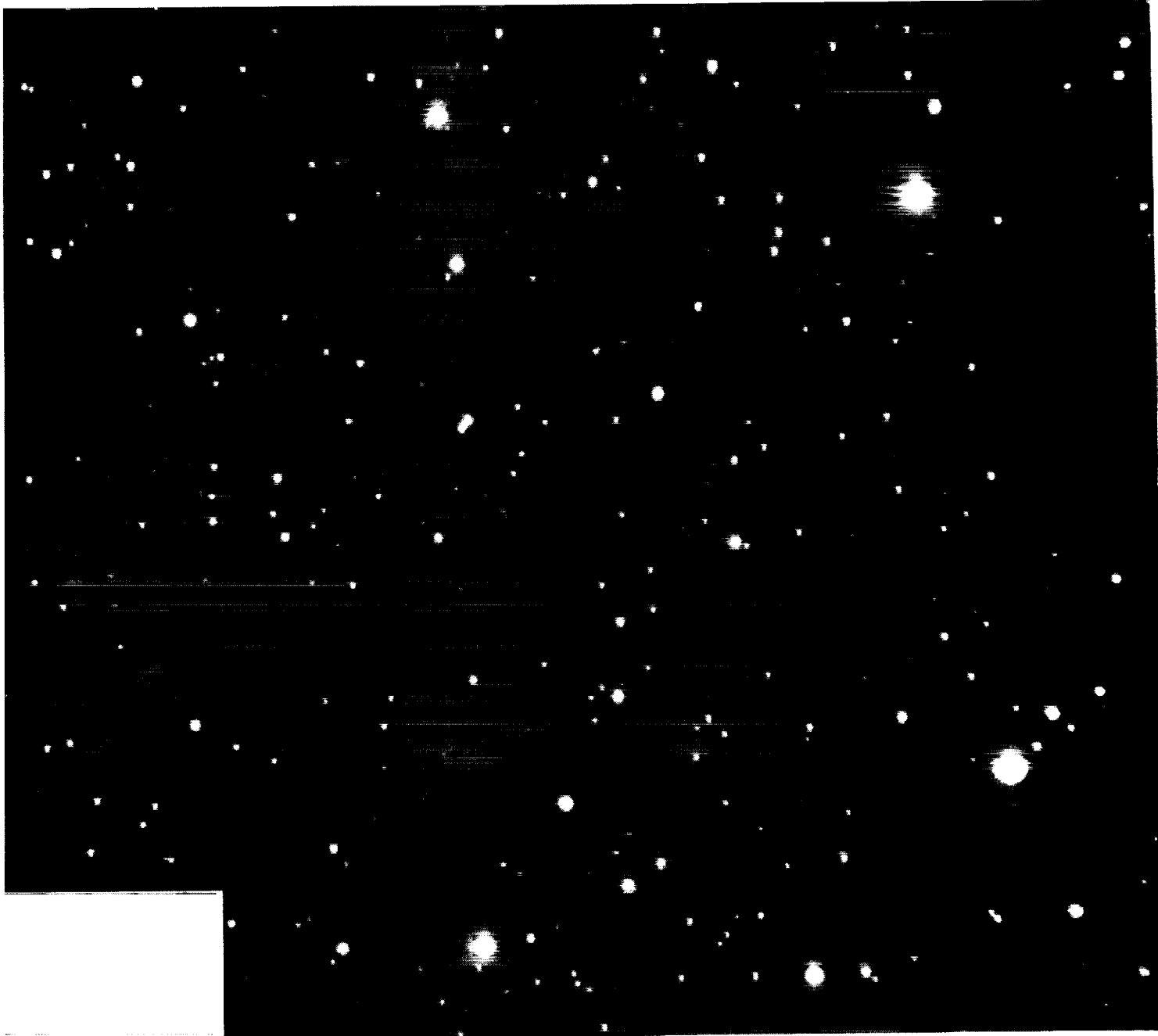
Right: A console is available for astronomers who wish to be present when their programmed observations occur. Some direct commanding is possible to control instrument settings and final positioning of the astronomical target in the field of view.

(NASA)

To use the Hubble Space Telescope, an astronomer need not leave home. This orbital observatory is almost totally preprogrammed, and its operation involves complex command procedures that are the business of engineers in the Space Telescope Operations Control Center. The astronomer interacts with the Space Telescope Science Institute, not directly with the observatory or its control center. The Institute is responsible for science planning and scheduling and for science data processing and archiving.



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Like an observer at a ground observatory, the Hubble Space Telescope guest observer must request observing time well in advance. However, because of the complexities of scheduling an orbital telescope, the lead time between request and observation is much longer, and the astronomer must describe the observing plan in much greater detail. Proposals for observations are submitted to the Institute, evaluated by peer review, and selected as much as a year or two before the actual observation occurs.

During the interim, the observation plan is refined, and all activities necessary to accomplish it are specified. The Science Institute then begins to compile a master calendar, usually six months at a time, to schedule the selected observations.

Because observation time in space is costly, the governing philosophy in scheduling the Hubble Space Telescope is efficiency. The aim is to maximize the time on target and minimize the time spent reorienting the telescope from target to target.

Thus, observations of stars and galaxies located in the same part of the sky are generally scheduled together. If an astronomer wants to observe objects in different parts of the sky, these observations probably will not occur successively in one orbit nor even in one day or week. An astronomer's plan may be split up and scattered throughout the six-month period to improve overall scheduling efficiency.

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Observing with the Hubble Space Telescope

Likewise, if an astronomer's program requires a long observation, perhaps three hours on a target, the observation may be interrupted as the view from the orbiting telescope is blocked by the Earth or as some other activity takes precedence.

Although the telescope operates around the clock, not all the time is spent in observing. Each orbit lasts about 90 minutes, with time allocated both for housekeeping functions and for observations. "Housekeeping"

includes turning the telescope to acquire a new target or avoid the sun or moon, switching communications antennas and data transmission modes, receiving command loads and downlinking data, calibrating, and similar activities.

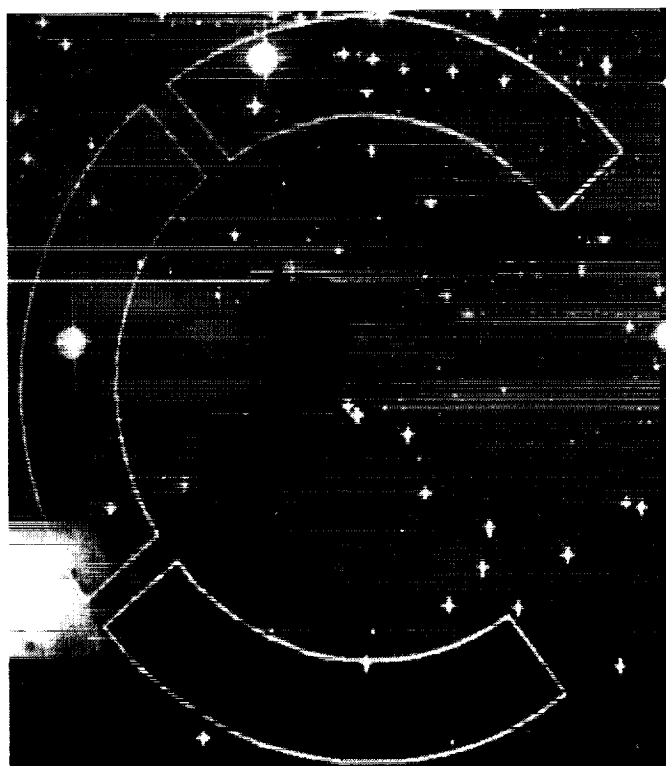
When the Science Institute completes its master observing plan, the schedule is forwarded to Goddard's Space Telescope Operations Control Center, where the science and housekeeping plans are merged into

a detailed operations schedule. Each event is translated into a series of commands to be sent to the onboard computers. Computer loads are transmitted ("uplinked") several times a day to keep the telescope operating efficiently.

Normally, two of the scientific instruments will be used simultaneously to observe adjacent target regions of the sky. For example, while a spectrograph is focused on a chosen star or nebula, one of the cameras will be photographing a sky region offset slightly from the main viewing target. During observations, at least two of the three Fine Guidance Sensors will be operating, each tracking a separate guide star to keep the telescope pointed steadily at the right target.

If an astronomer desires to be present during his or her observation, there is a console at the Science Institute and another in the Control Center, where monitors display images or other data as the observation occurs. Some limited real-time commanding for target acquisition or filter changing is performed at these stations, if the observation program has

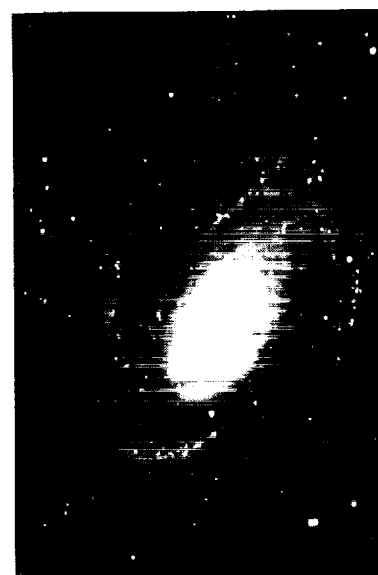
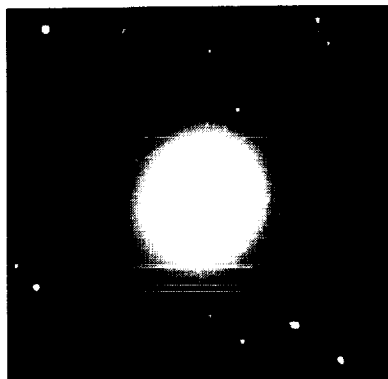
been set up to allow it, but spontaneous control is not possible. For some investigations, the observer may make fine adjustments to the telescope's pointing, using a light pen and cursor to center within an aperture a small target in a wider field. Whether or not the guest observer is present at the Institute, a staff astronomer and console operator are on duty at all times to monitor the observations. This is where real



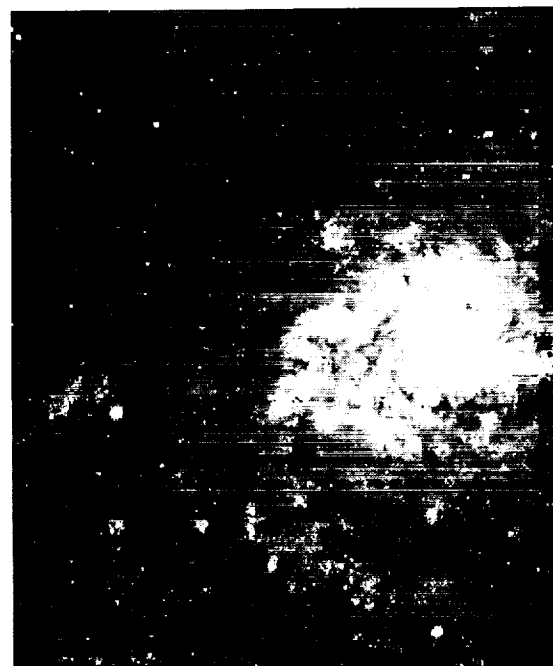
The fields of view of the Fine Guidance Sensors form three "pickles," here superimposed on the Horsehead Nebula in Orion. To acquire an object for observation, the telescope must first locate appropriate guide stars with two of the three Fine Guidance Sensors. Candidate guide stars are shown as yellow crosses. The guide star catalog includes almost 19 million objects.

(Space Telescope Science Institute)

Giant elliptical galaxy M87 in Virgo
(Kitt Peak National Observatory)

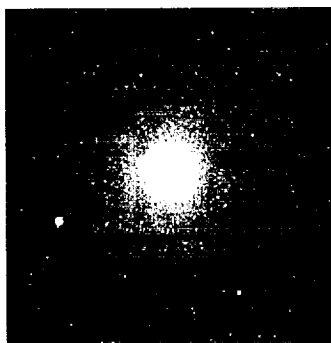


M81 galaxy in Ursa Major
(Kitt Peak National Observatory)



excitement is felt as astronomers have a first look at what the telescope sees. The initial images and data are soon processed and refined by sophisticated computer programs on the ground.

In a much larger room at the Space Telescope Operations Control Center, 30 miles away, consoles are manned around the clock as operators stay in constant contact with the observatory, sending up commands,



Globular star cluster in Pegasus, M15
(Kitt Peak National Observatory)

monitoring status, and receiving downlinked data. This is the nerve center. Behind the scenes at the Goddard and Marshall Space Flight Centers and at the industry sites where the telescope and its parts were developed, support teams stay on call to respond to any operational problems that may occur.

Engineering and scientific data from the observatory, as well as uplinked operational commands, are transmitted through the Tracking and Data Relay Satellite System (TDRSS) and its companion ground station at White Sands, New Mexico. Up to 24 hours of commands can be stored in the onboard computers. Data can be broadcast from the telescope to ground stations immediately or stored on tape and downlinked later.

The observer on the ground can examine "raw" images and other data within a few minutes for quick-look analysis. Within 24 hours, Goddard formats the

data for delivery to the Institute. The Science Institute is responsible for data processing; it calibrates, edits, distributes, and maintains data for the scientific community. The guest observer may analyze the data with software provided by the Institute or with his or her own programs, and the data may be analyzed at the Institute or at the observer's home institution. Eventually, observers around the world will be networked to the Institute, enabling them to have keyboard access to the data archives there.

Competition is keen for observatory privileges on the ground and in space, there being far more astronomers than large telescopes. The line to use the Hubble Space Telescope is already long, and for every one observer whose proposal is accepted there may be ten others waiting.

Most modern observatories are cooperatively used as national and international

research centers. The Hubble Space Telescope will be operated in this tradition, as a resource for astronomers worldwide. Some observing time is allocated for amateur astronomers, as well. Data will be maintained in the Institute's archives and, when the primary investigators' research is completed, made available to all astronomers, not only those whose observations are accepted but also those who are waiting.

The perplexing problems in astronomy today cannot be resolved by a single instrument, a lone observer, or even one observatory. The new breakthroughs in theory and understanding are likely to come as a result of complementary investigations, involving several different instruments, observers, and observatories on the ground and in space. The Hubble Space Telescope program is organized to encourage collaboration and discovery.



M33 galaxy in Triangulum
(Kitt Peak National Observatory)



Data from the Hubble Space Telescope will be relayed by satellite and ground stations to the Goddard Space Flight Center for processing and then to the Space Telescope Science Institute in Baltimore, where the archives will be maintained. (NASA)

Servicing in Space

Two astronauts are absorbed in a task they have rehearsed for months: servicing the Hubble Space Telescope. Like members of a surgical team, each anticipates the action of the other and offers the proper tool or equipment as it is needed. They work quickly and with the confidence that comes from practice.

The Hubble Space Telescope rises like a tower from its repair platform in the Shuttle. The observatory is temporarily closed down, its solar arrays and antennas retracted and the aperture door closed. The immediate purpose of this servicing mission is to replace several batteries and sensor units that are reaching the end of their limited lifetimes.

Like an observatory on Earth, the Hubble Space Telescope can be repaired. As equipment wears out or becomes obsolete, it will be replaced. Already another observatory, the Solar Maximum mission, has been successfully repaired in space to extend its operation for several more years. The ability to service observatories in orbit is an important new way to extend their useful lifetimes. Servicing in space protects our substantial investment in technology to answer the highest priority questions in modern astronomy.

Routine service calls at the Hubble Space Telescope are scheduled at approximately three-year intervals to replace batteries and other limited-life items. These items, called Orbital Replacement Units, include components in the guidance and control systems and in the command and data handling system, a computer, solar arrays, and the scientific instruments. Altogether, some 70 items in the Hubble Space Telescope can be replaced in orbit. The particular set of replaceable items varies



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Astronauts test servicing procedures with flight hardware on the ground to be certain that tools, fasteners, and other equipment fit and operate properly for servicing in orbit. More than 80 tools, including common screwdrivers and wrenches, are available.

(Lockheed)



**Like an observatory on Earth,
the Hubble Space Telescope
can be repaired. As equipment
wears out or becomes obsolete,
it will be replaced.**

from mission to mission, depending on the condition of the observatory.

A repair mission begins with detailed planning and training on the ground, followed by a rendezvous in space. The Shuttle crew maneuvers to the telescope, captures it using the robot arm, brings the telescope aboard, and attaches it to a maintenance platform in the payload bay. There the telescope remains for several days while astronauts inspect it and exchange equipment.

The replacement units are readily accessible behind doors in the telescope shroud. Ranging in size from a shoebox to a telephone booth, most of the items can be removed or installed with the aid of wrenches and screwdrivers. Other crew aids include portable lights and foot restraints, small platforms that give the astronaut a stable foot-hold for the business of disconnecting electrical cables, disengaging latches and bolts, and replacing various pieces of equipment.

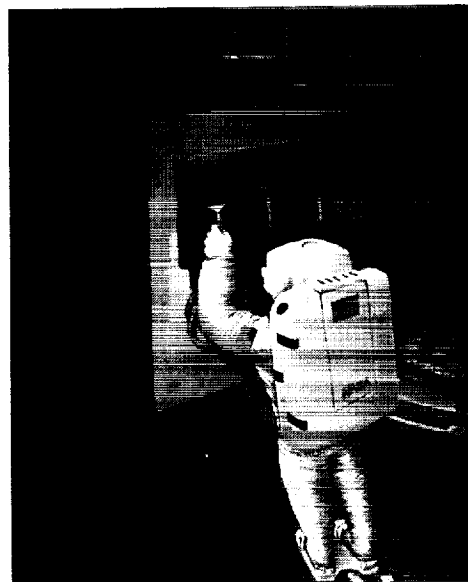
While attached to the maintenance platform, the repaired telescope undergoes status monitoring and checkout exercises, controlled by commands from the ground. If an orbit boost is necessary, the crew takes the Shuttle to a higher

altitude for redeployment. Once again, the robot arm is used to lift and guide the telescope out of the payload bay. The solar arrays and antennas are extended again, the power is turned back on, and the telescope is released to resume operations.

If any problems arise during the redeployment, the Shuttle crew can retrieve the telescope and manually override a faulty mechanism. If the problem can-

not be solved, the Hubble Space Telescope may be brought home. If all occurs according to plan, the telescope will remain in orbit, doing its work until the next scheduled servicing mission.

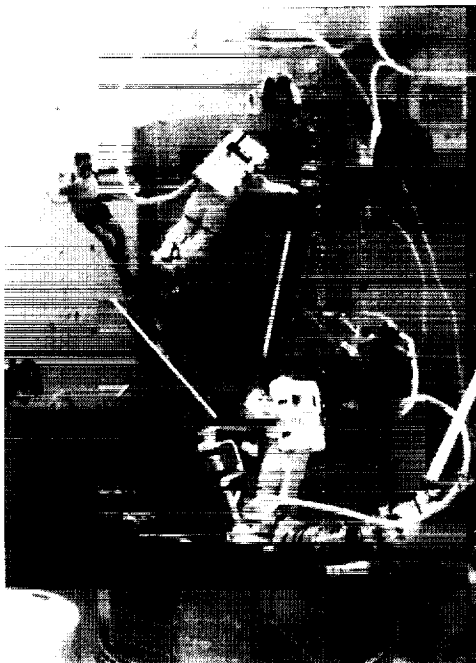
The Hubble Space Telescope is the first observatory designed for extensive maintenance and refurbishment in orbit. A long-lived mission is scientifically necessary for both discovery and detailed follow-up study. ☺



Many parts of the Hubble Space Telescope, such as the batteries, are designed to be removed and replaced. (Lockheed)



Large units, such as the Fine Guidance Sensors and scientific instruments, also can be removed for servicing or replacement. (Lockheed)



Servicing procedures are rehearsed underwater to simulate the weightless environment of space.

(NASA)

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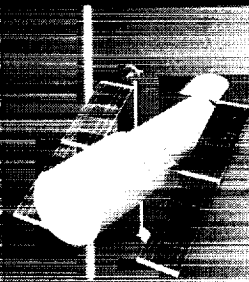
SPACE OBSERVATORIES OF THE NEW ERA OF ASTRONOMY

1989

1991

1993

1995



HUBBLE SPACE
TELESCOPE

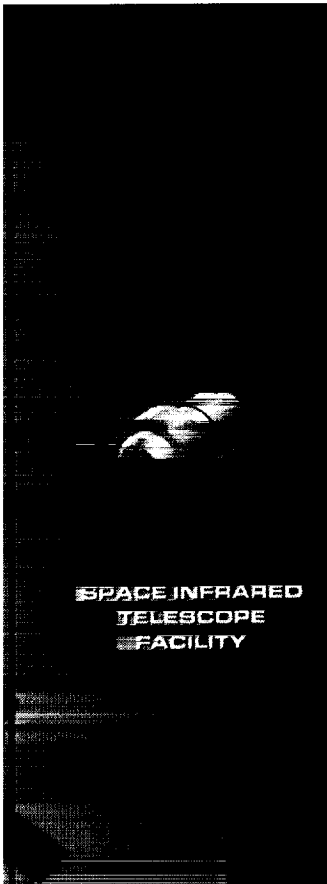


GAMMA RAY
OBSERVATORY

ADVANCED X-RAY
ASTROPHYSICS
FACILITY

Opportunities for Discovery

Curiosity and technology: these are the prerequisites for modern astronomy and astrophysics. We question the cosmos, but most of the answers lie beyond the range of our observational tools. Many discoveries await the development of new technology for more precise measurements.



The Hubble Space Telescope is the first in a new family of Great Observatories designed to explore the universe across the electromagnetic spectrum.

(NASA)

In just the past 40 years, the pace of discovery has dramatically accelerated as astronomers have taken advantage of rapid developments in technology. As a result, we now know that the universe contains not only the familiar planets, stars, and galaxies observed for centuries but also a rich variety of objects discovered quite recently. Quasars, pulsars, radio galaxies, X-ray stars and galaxies, infrared stars and galaxies, and gamma ray bursts have been identified in our lifetimes with technology that was not previously available. Some anticipated objects, such as black holes, have not been observed directly; their discovery requires techniques not yet in use today. Other objects not yet imagined await revelation by new instruments.

The Hubble Space Telescope is an instrument for discovery and prolonged study. Despite decades, even centuries, of curiosity, only now has the technology become available to build such a sensitive observatory and put it above the atmosphere. Advances in mirror, detector, materials, and space transportation technologies together make the Hubble Space Telescope possible in our lifetime. We will witness the new astronomy.

In the past 15 to 20 years while the Hubble Space Telescope was being designed and developed, progress in technology has marched on. Already, new detectors are becoming available, and the program includes development of "second generation" scientific instruments. After 5 to 6 years in orbit with its present instrument complement, the observatory may be refurbished in space. Some of the scientific

instruments may be removed and replaced with new state-of-the-art detectors to extend our range of observation again. Just as the 40-year-old telescopes at Mount Palomar remain premier observatories through periodic upgrading with new technology, so the performance of the Hubble Space Telescope will keep pace with technological advances.

The Hubble Space Telescope is a key element in a broad campaign to observe the universe across the electromagnetic spectrum. This observatory will not be used in isolation but will be complemented by other telescopes sensitive to different wavelength bands. All matter radiates energy at different wavelengths, depending on the temperature of the matter. A telescope is, in a way, a remote thermometer detecting radiation within a specified wavelength (temperature) range. Because the spectrum from radio waves to gamma rays is so broad, no single telescope can detect all types of radiation or all objects.

Thus, NASA's strategy for astrophysics research is to launch a family of telescopes, the "Great Observatories," each tuned to a different channel of the spectrum. The Hubble Space Telescope is the flagship, to be followed by the Gamma Ray Observatory, and later the Advanced X-ray Astrophysics Facility and the Space Infrared Telescope Facility. These large observatories in space will operate for the next few decades. Together, they will give us a comprehensive look at the universe in all its guises.

What we now know, though exciting, is probably less interesting than what we are about to learn. Where is technology leading astronomy? What new questions may be asked in the

next generation? We can hardly guess today, but they will be guided by the Hubble Space Telescope, which will surely introduce us to objects and phenomena that we have not yet imagined. The really intriguing questions are the ones we don't even know to ask.

There is no doubt that our knowledge of the universe is going to change, perhaps as dramatically as it did when Galileo's telescopes confirmed Copernican theory that the Earth was not, after all, the center of the cosmos and that the Milky Way contained far more stars than anyone had ever suspected. The repercussions of these discoveries were felt throughout western civilization, not only in science but also in art and literature, philosophy and theology. We may enter the 21st century with radically altered perceptions of the universe, its origin, extent, contents, fate, and our place in it.

We are intrepid explorers, observing the distant stars and galaxies because our technology will not yet take us there. Until we can roam freely through the universe, we continue to explore it by capturing its light. Through the Hubble Space Telescope, many of those specks of light will become discernible objects—stars, galaxies, quasars, maybe planets and exotic things that we have never seen before.

This book is but a prelude; the next edition will present the universe newly revealed by the Hubble Space Telescope. We stargazers are eager to see!



Palomar Observatory

Hubble Space Telescope (Joe Boyer, artist; Lockheed)



**The
Hubble
Space
Telescope:**

Engineering Challenge

The problem of designing an observatory more capable than the best optical observatories on the ground but packaging it compactly enough to fit into the Space Shuttle and adapting it to operate while orbiting Earth every 90 minutes is not hypothetical. Engineers faced precisely that challenge in designing and fabricating the Hubble Space Telescope.

Imagine a building that contains all the mirrors, cameras, detectors, and computers for a high-precision observatory, plus all the supporting utilities (electrical power, temperature control, pointing mechanisms) and a communications center for telescope command and data flow. At Mount Palomar, such an observatory is a 12-story building, but the space available for the imaginary facility is about the size of a railroad car or an 18-wheeler truck, and its total weight is severely restricted to less than 13 tons.

Then imagine that the building is in motion, moving so rapidly that night falls every hour and a half and lasts only 45 minutes. Despite its motion, however, the entire structure must be pointed toward a particular celestial object within a field of view as small as the full moon appears to be and held so still that very faint light from an object billions of light years away will enter the telescope and pass precisely through the center of a small hole to fall upon a detector. The least tremor will result in a loss of information and detail.

Designing and developing the systems for the most complex satellite ever placed in orbit presented extraordinary engineering demands. How was the Hubble Space Telescope designed, and how does it work? What was difficult about this particular telescope? The optical system, which collects and focuses light, and the pointing control system, which acquires the astronomical target and keeps the telescope "locked" on it: these were the primary technical challenges.

The primary mirror is coated with a layer of reflective aluminum (2.5 millionths of an inch), protected by a 1-millionth-inch layer of magnesium fluoride. It is the smoothest, most uniformly coated large mirror ever made. (Perkin Elmer Corp.)

In Focus

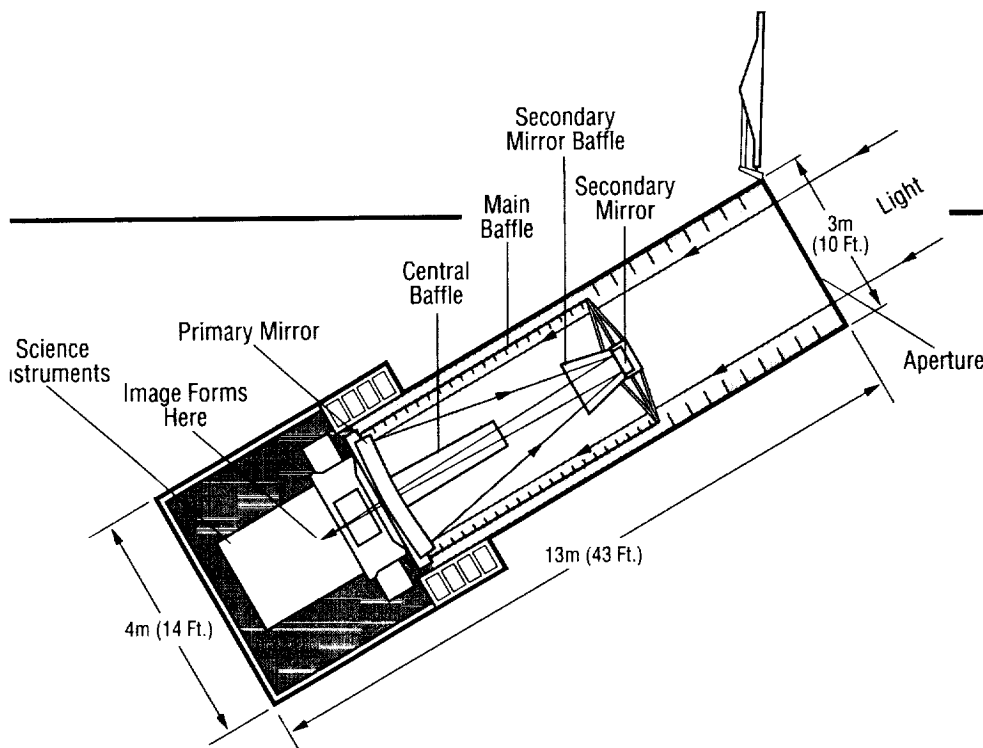
Telescopes collect light from a distant stellar source and concentrate the light onto a spot, preferably as small a spot as possible. As light travels away from its source, it spreads out in an expanding sphere, just as a balloon covers a larger and larger area as it is inflated. A tele-

scope can be thought of as a "light bucket"; the primary mirror or lens is the collecting surface. The larger the mirror or lens, the more expensive and difficult it is to make.

The aim of mirror design is to reflect all the collected light through the optical system and concentrate it onto a very small

spot. For a single star, the spot is smaller than the period at the end of this sentence. The telescope also forms images of planets, galaxies, nebulae, and other extended sources that cover a larger area of the focal plane. The larger the mirror that collects light, the sharper the image of the distant object that





Layout of the Optical Telescope Assembly

is the light source, if the mirror is very smooth. The mirror should be very smooth because any surface ripples or bumps degrade the image in the focal plane. The more bits of light (photons) that arrive at one spot, the brighter the image. The smaller the spot of concentrated light, the sharper the image and the fainter the source that can be detected.

An optically perfect mirror concentrates light to the smallest spot possible, limited only by the wave nature of light itself and not by engineering imperfection. Early in the planning, NASA and the scientific community determined that the Space Telescope should be diffraction limited; that is, the deviation from perfection would be imposed by light, not by hardware. At the time, the technology did not exist to achieve this degree of optical perfection

for a large mirror. The mirror foreseen for the Hubble Space Telescope was beyond the state of the art.

Besides being large and extremely smooth, the mirror had to be lightweight. The weight-to-orbit capability of the Space Shuttle or any other launch vehicle is limited, so every pound is critical. The 200-inch mirror at Mount Palomar weighs 14.5 tons; the 94.5-inch Hubble Space Telescope primary mirror had to weigh less than 1 ton. Engineers cleverly eliminated about 75% of the glass that would have been required in a solid mirror of this size by designing the Hubble mirror as a honeycomb structure. If it had been fabricated as a solid, the Hubble mirror would have weighed about 3 tons.

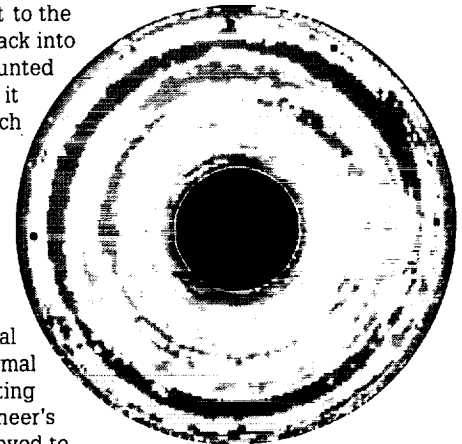
The Hubble mirror also had to be thermally stable, invulnerable to expansion and contrac-

tion as the telescope repeatedly passes from dayside heat to the frigid orbital night and back into sunlight. It had to be mounted rigidly enough to protect it from damage during launch vibrations but not so rigidly to warp or deform it. The telescope built on Earth had to be designed to operate in the much different environment of space. This combination of requirements for optical quality, light weight, thermal stability, and rigid mounting could have been an engineer's nightmare. Instead, it proved to be the stimulus for creative solutions.

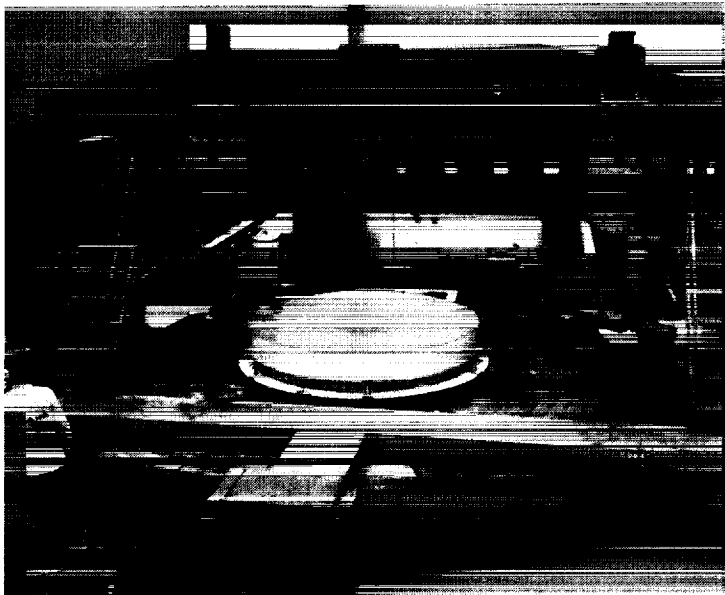
Another requirement complicated the fabrication. The scientific community wanted a versatile large space telescope that operated not only with visible light but also with ultraviolet. Because each portion of the spectrum demands a different type of mirror coating, the design of the Hubble Space Telescope required engineering trade-offs and compromises. For example, aluminum is the best



The primary mirror surface must be virtually perfect. In these computerized maps of the mirror, the ideal surface is white. Meticulous polishing smoothed away high (blue) and low (red) variations in the surface. (NASA)



The requirements for optical quality, light weight, thermal stability, and rigid mounting were a stimulus for creative solutions.



A special computer-controlled machine was designed for the grinding and polishing process. Final polishing was done by hand.

(Perkin Elmer Corp.)

Development of the Hubble Space Telescope is a story of innovative engineering and technology.

coating for visible light astronomy, reflecting up to 99.5% of the light, but it alone reflects almost no ultraviolet radiation. Aluminum oxidizes rapidly and must be protected by an overcoating in order to reflect ultraviolet. Furthermore, the overcoating must be just the right thickness to be transparent to both ultraviolet and visible light.

Given the different scientific objectives for the observatory,

the solution was an aluminum layer with a magnesium fluoride overcoating to protect the mirror surface and optimize performance in the ultraviolet range. A slight overcoat of magnesium fluoride, much thinner than this sheet of paper, protects against oxidation and increases ultraviolet reflectivity to about 75%, but it decreases visible reflectivity to 85%. Though decreased from ideal, performance in the visible range is still quite satisfactory.

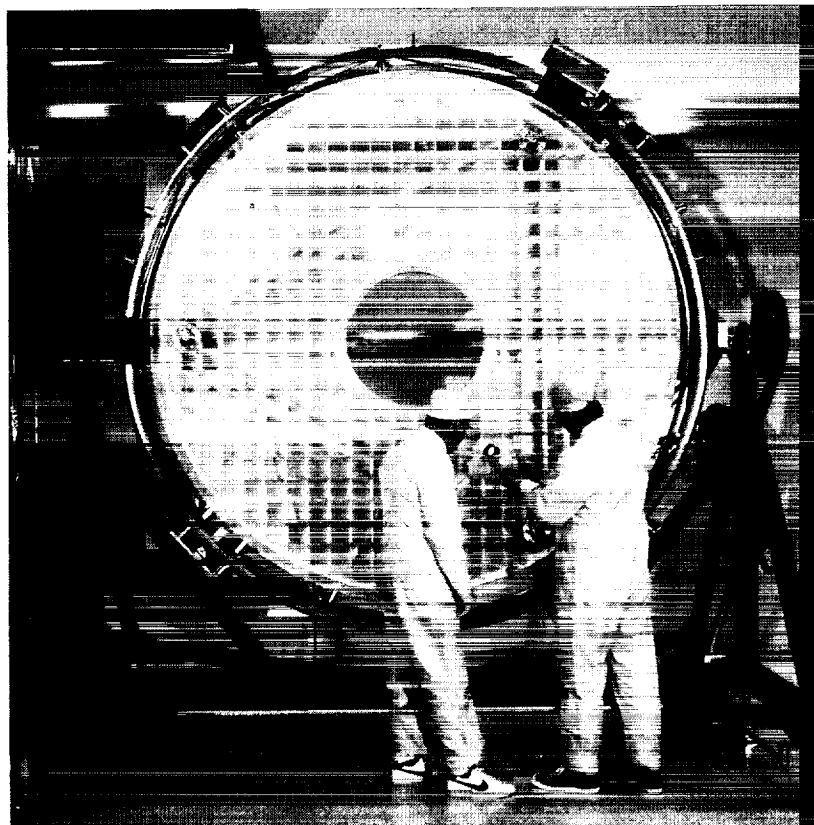
The coating process was particularly demanding because both coatings had to be extremely uniform for proper reflection, and they had to be applied in a high vacuum within a matter of seconds to avoid oxidation. Furthermore, the thinness of the magnesium fluoride overcoat had to be precisely controlled to achieve the desired ultraviolet reflectivity. A special chamber and equipment were prepared for the extremely delicate coating process, and technicians rehearsed the 10-second procedure for a year.

Development of the Hubble Space Telescope optical system advanced the state of the art in several disciplines. The mirror and optical system of the Hubble Space Telescope are the best that exist at their size. The 2.4 meter (94.5 inch) primary mirror is an efficient reflecting surface for visible light and is less effective but acceptable for ultraviolet. It is polished so smooth that the surface varies less than a millionth of an inch. The optical path is optimal for concentrating light from a single star at the focal plane.

Achieving this optical quality required new techniques of mirror fabrication, grinding and polishing, cleaning and coating, as well as highly precise analysis techniques to verify the uniformity and quality. To meet the weight, thermal, and mounting specifications, new materials and designs had to be devised, tested, and used. Each element is a story of innovative engineering and technology.

The inner honeycomb structure was visible before the mirror was coated.

(Perkin Elmer Corp.)



While it awaited launch, the Hubble Space Telescope was kept meticulously clean. The mirror is extremely sensitive to contamination. Like a sunscreen that blocks ultraviolet rays, a coating of oil a few molecules thick on the magnesium fluoride would destroy its ultraviolet reflectivity. Grains of dust on the mirror would scatter light, producing a background haze that would limit the telescope's ability to detect faint objects. Components were "baked out" in a vacuum to get rid of vapors that would "outgas" and contaminate the optics in orbit.

Extraordinary precautions were taken to keep the telescope clean during assembly and checkout before flight. The chamber where it was kept was thousands of times cleaner than a typical laboratory. Temperature, humidity, and air flow were precisely controlled, and the air was thoroughly filtered. Technicians abided by a strict dress code and cleansing protocol to avoid bringing any contamination into the area. All materials, tools, cameras, even checklists used during the preflight assembly and testing had to be cleaner than clean.

Designing, developing, and assembling the optical system was a challenge faced on the ground, where people and machines could be used to solve the engineering problems as they arose. The telescope operates in space, however, far beyond the immediate reach of helping hands. The pointing control system was another complicated engineering assignment.

The Hubble Space Telescope was assembled and tested in a protected environment. Here the optical telescope and focal plane structure is visible before the outer shell was installed.

(kheed)



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Still Light

Everyone who has tried photography knows the difficulty of holding a camera still and the disappointment of blurred images if the camera moves. The problem of jitter is magnified in telescopes, which require long exposures, sometimes hours, on the same object to produce images bright enough to detect. As the Earth turns, the star or galaxy being observed seems to move across the sky, so telescopes on the ground have to move slightly during an exposure to compensate for the Earth's rotation.

A telescope must be able to lock onto a target of observation and hold the image still within the field of view, even as the instrument itself moves ever so smoothly to track the object.

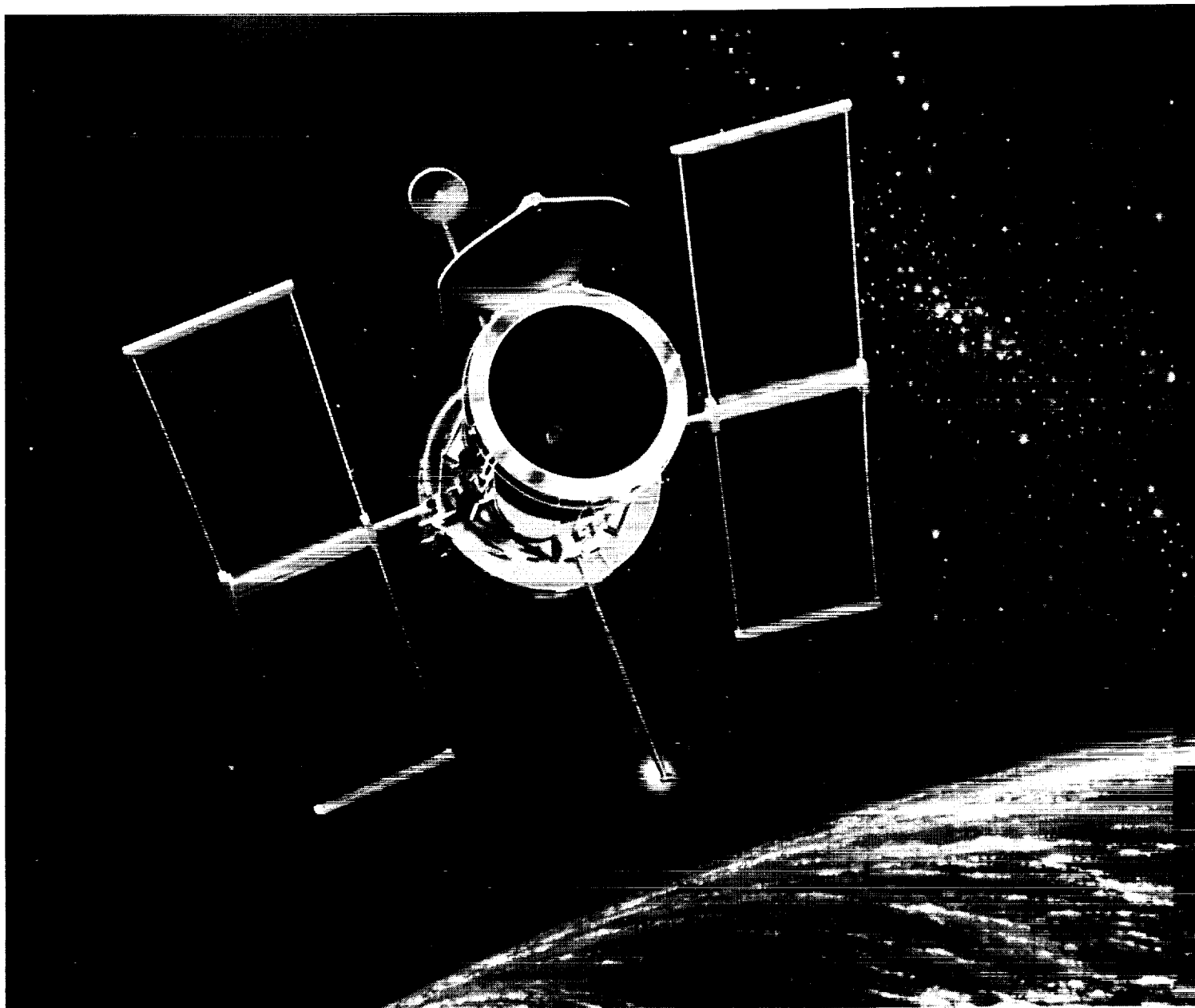
Finding the astronomical target, locking onto it, and holding the image still is not an easy task on the ground, but the difficulty is compounded in an orbital telescope. On Earth, we use the bedrock of a mountain-top to steady a telescope, but what steadies a telescope in space? The Hubble Space Telescope is stabilized by a highly sophisticated dialogue

The Hubble Space Telescope is the most precisely pointed machine ever devised for astronomy.

between complex computer programs and control mechanisms.

The Hubble Space Telescope is the most precisely pointed machine ever devised for astronomy. Its requirements for pointing stability and pointing accuracy are expressed in terms

of multiple-zero decimals. The telescope must be able to maintain lock on a target for 24 hours without deviating more than $7/1000$ ths (0.007) of an arc second (2 millionths of a degree), about the width of a hair seen at a distance of a mile. Like the optical



system, the pointing control system stretched the state of the art to achieve this degree of accuracy.

The pointing control system comprises several different elements all working together to maneuver the telescope, guide it toward observation targets, and hold it steady. Maneuvers, or slews, are governed by reaction wheels, which generate control torques that turn the telescope, and rate gyros, which give the computer information about the telescope's orientation or attitude. The telescope can be maneuvered a quarter-turn (90 degrees) with the required accuracy and stability in about 18 minutes, moving slightly slower than the minute hand of a clock. The rate gyros report 40 times per second, and they are sensitive enough to detect position changes as small as .00025 arc second (7 hundred-millionths of a degree). Thus, they are also crucial in fine pointing during target acquisitions and observations.

During routine operations, three types of position indicators provide the information needed to point the telescope: the fixed head star trackers which are independent of the main telescope optics and can locate bright stars to a precision of about 1 arc minute (1/60th degree); the rate gyroscopes that provide precise angular measurements for short-term stability; and the fine guidance sensors which derive their signals from stars imaged near the edge of the telescope's field of view. The pointing control system uses four of six rate gyros and two fine guidance sensors to provide roll, pitch, and yaw information and keep the observatory locked on a celestial object.

Telescope motions are controlled by varying the speed of spinning reaction wheels. The reaction wheels receive commands from an onboard

computer to generate torque, the force that produces rotation, and point the telescope to a given position with an accuracy of 0.01 arc second or less. The signal for these wheels is derived from a variety of sources—a coarse sun sensor, fixed head star trackers, gyroscopes, and interferometric star trackers—all processed by the flight computer. Four magnetic torquer bars on the exterior of the telescope, also controlled by computer, react against Earth's magnetic field to limit reaction wheel speed.

Target acquisition is governed primarily by the fine guidance sensors, which search for guide stars that will bring the target of observation into the instruments' field of view. Three fine guidance sensors have a horseshoe-shaped field of view at the perimeter of the focal plane. The master "reference book" for telescope pointing is the guide star catalog, a compendium of almost 19 million recognizable objects whose positions are known to about 1 arc second (3 ten-thousandths of a degree). The telescope uses guide stars rather than the actual observation targets for pointing. For any selected target of observation, the fine guidance sensors seek out guide stars that will bring the target precisely into the center of the selected detector's field of view. Each observation target is keyed to multiple guide stars, depending on the telescope's orientation, where it is in its orbit, and which detector is being used.

To acquire a target, two of the three fine guidance sensors must lock onto guide stars. The process of a typical target acquisition begins with a slew of the telescope to a predetermined position. The fixed head star trackers are used to determine the rough position of the telescope. Then the coordinates of a candidate guide star are fed

into each of two fine guidance sensors. One sensor begins to seek the first guide star, searching in a spiral pattern until the proper star is found. Upon finding a star in the correct brightness range, it stops and the other sensor searches for another guide star. When the second star is found, the relative positions provide the final confirmation of position. If the position is not confirmed, the search resumes. The acquisition cycle typically takes about 20 minutes; in some cases, alternate methods may be used to reduce the acquisition time.

Once the guide stars are acquired, their light passes to a prism interferometer that provides a tracking signal. The basic stability reference is the set of rate gyros with positions that are updated every second by the fine guidance sensor signal.

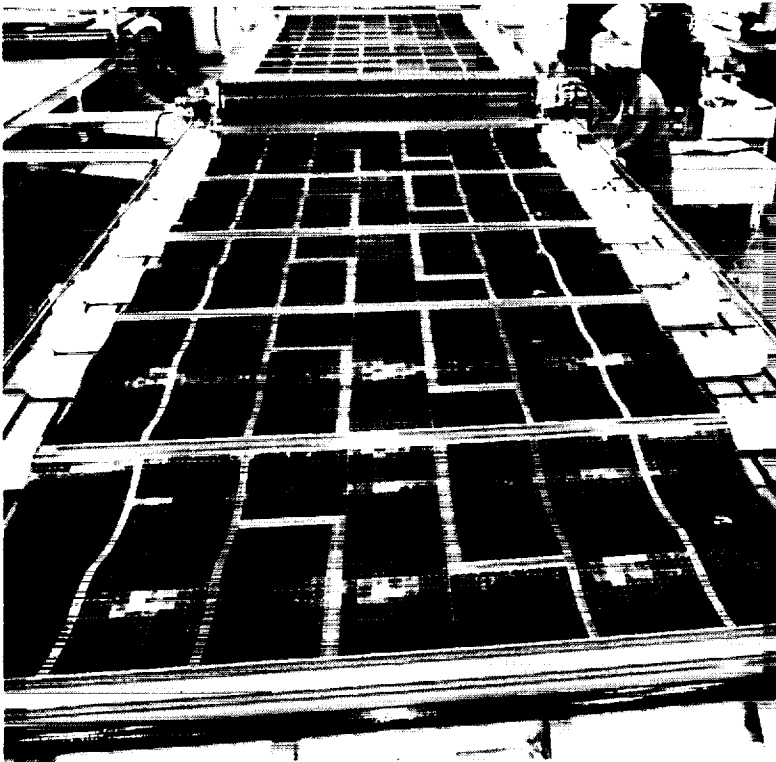
The telescope locks onto the guide stars that bring the selected target into the field of view of the selected instrument. Each instrument has a method of automatically centering the science object in its aperture or sending down a real-time signal which will allow the observer to make a final decision on the exact pointing. In addition, the Wide Field/Planetary Camera can be used to make a quick image from which the position of the science target with respect to the guide stars can be determined, either in real time or later in the observing sequence. When the telescope locks on a target, the resulting stability enables high-resolution (fine detail) visible and near-ultraviolet images.

Three elements have to be held completely stable, with no jitter or disturbance whatsoever: the focal plane and both the primary and secondary mirrors. The biggest challenge for engineers and designers of the pointing and control system was to identify and control all line-of-sight disturbances that



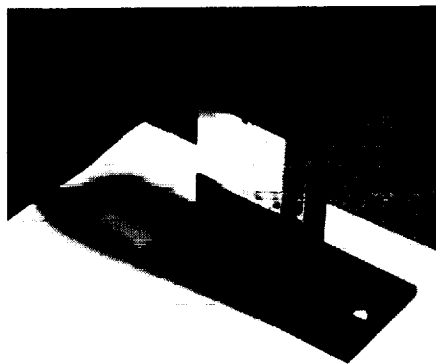
Focal plane and Fine Guidance Sensor fields of view ("pickles") superimposed on the Andromeda Galaxy, M31

(Space Telescope Science Institute)



One of the two delicate wings of the solar array (NASA)

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Fine Guidance Sensor prism
(NASA)


might compromise the telescope's stringent requirements for pointing accuracy and stability. Some sources of error are in the equipment and can be controlled; for example, noise or vibrations from onboard electronics or thermal flexing can introduce random errors into the attitude and pointing signals. If the telescope jerks during a maneuver, the solar arrays will respond with a low-frequency wave that takes a long time to disappear. Gyroscopes "drift" and need frequent correction.

Over a longer time, a major temperature change brought about by telescope maneuvers may cause a long-term change in structural dimensions, which can have a significant degrading effect on precise observations. Therefore, all parts sensitive to temperature changes had to be made thermally stable; the truss structure, focal plane, and secondary mirror support were thus made of graphite-epoxy, a material that barely deforms as the temperature changes. Many elements also have thermostats and heaters to maintain active thermal control.

Other sources of error are environmental and must be compensated for, if not controlled. For example, the telescope is affected by a slight aerodynamic force and gravitational torque as it moves around Earth. Torques that act on the spacecraft must be nullified by the momentum management system to hold the telescope steady.

To attain the specified pointing stability and accuracy, several technological advances were required, particularly in the development of vibration-free equipment. The bearings in the reaction wheels, for example, had to be the best ever manufactured for perfect balance, and isolators were added in the reaction wheel assemblies to dampen any vibration. Likewise, the onboard tape recorders had to operate very smoothly and quietly.

The most demanding achievement in the pointing and control system was design and fabrication of the Fine Guidance Sensors, brand new systems capable of making extremely precise measurements to a milliarcsecond. Making glass prisms for the interferometers was an especially delicate and difficult effort. The two halves of each prism are held together without glue, bolt, or fasteners. They had to be smooth, so flat, and so clean they bonded by sheer molecular attraction. When held in the polisher's hand, the glass could be deformed merely by body heat. The prisms were almost impossible to make to the required perfection, and it took repeated trials before the sensors for flight (two per sensor) were produced. The Fine Guidance Sensors will define the state of the art for the foreseeable future.

The onboard computer is the brain for pointing and stabilizing the telescope. The computer contains the information required to operate the telescope for several days without contact from the ground, although initially a series of commands sent to the telescope every 24 hours. These instructions enable it to carry out a sequence of observations automatically. The computer executes commands to individual components in the various spacecraft systems at the proper time to accomplish the intended astronomical mission. Development and verification of the software code to perform all required functions were noteworthy achievements. 

Development of The Hubble Space Telescope

The idea for the Hubble Space Telescope has been around for quite some time. This observatory may be the most deliberately and thoroughly planned astronomy program of the century.

The Hubble Space Telescope concept has its origins in the writings of Hermann Oberth in the 1920's and Lyman Spitzer in the 1940's. These scientists suggested that astronomy could benefit greatly from a telescope that viewed the universe from above Earth's obscuring atmosphere.

In the early 1960's, after NASA's formation in 1958, interest increased in astronomy as a scientific discipline to be pursued from space, and momentum grew for development of a large orbiting telescope. In 1962, NASA asked the Space Science Board of the National Academy of Sciences to study and recommend future astronomy payloads. At this time, NASA was already studying a concept for an Orbiting Astronomical Observatory, a 0.75-m (30-in) telescope for ultraviolet observations. Two studies were made, one at the State University of Iowa and the other later at Woods Hole, Massachusetts. The decision of the two work sessions was split, with some members of the group proposing a much larger

telescope, (2.54 meters; 100 inches or more), and others dissenting on the basis that the smaller orbiting observatory would be temporarily satisfactory. Finally in 1965, a science board reviewed engineering studies and recommended that NASA develop a larger space telescope.

In the autumn of 1971, NASA began in earnest to do feasibility studies of the new telescope, then defined as a 3-m (10-ft) aperture telescope called the Large Space Telescope. The study results were favorable, and preliminary design was initiated in 1972. During this phase, the mirror size was reduced to 2.4 m (8 ft). The design study was continued until 1977, when Congress gave the approval to build and operate the observatory. By this time, the European Space Agency (ESA) had become a partner in the project, agreeing to provide the Faint Object Camera, the solar arrays, and staff support for telescope operations.

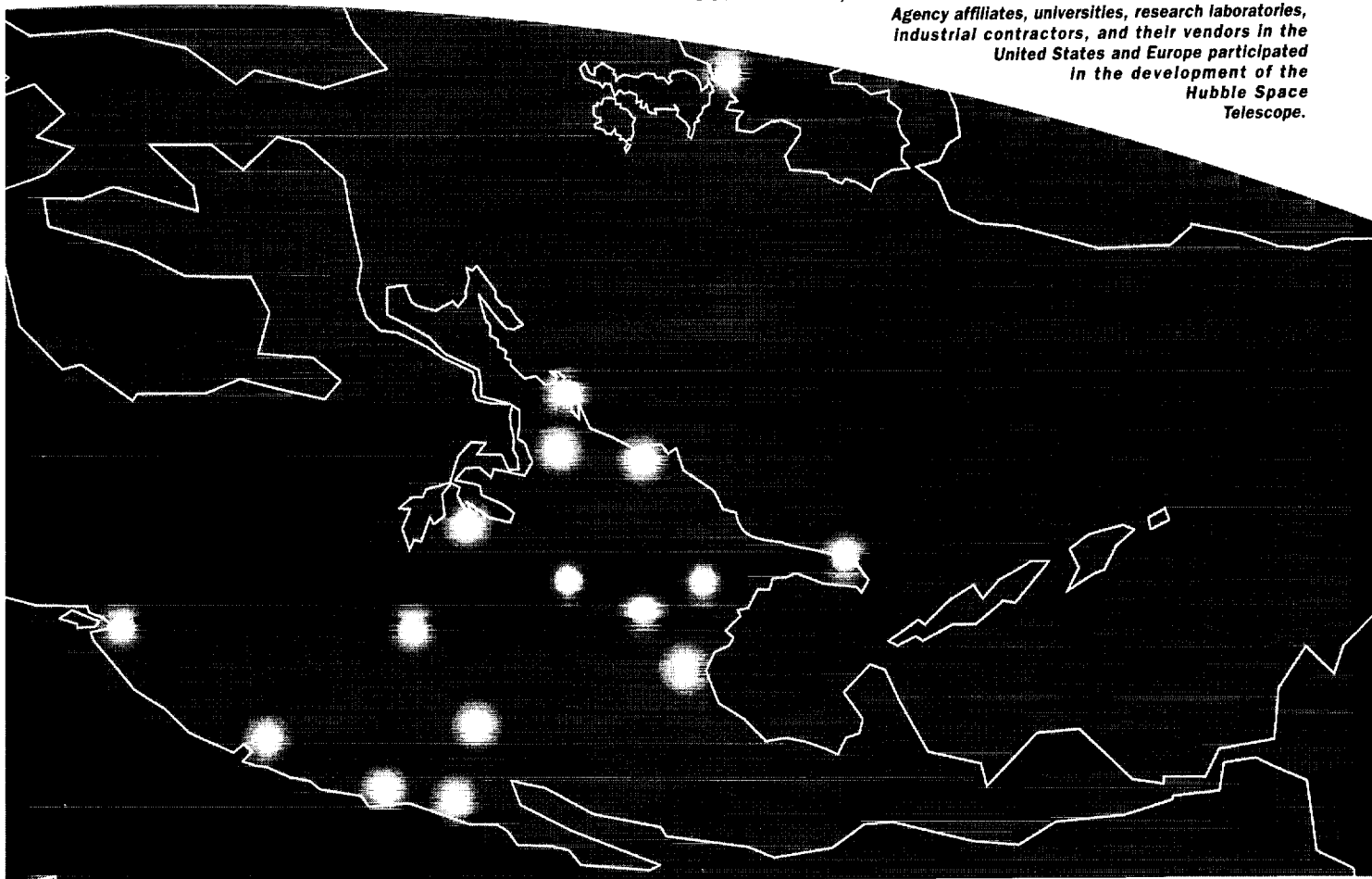
NASA selected two prime contractors to work on the Hubble Space Telescope project. Lockheed Missiles and Space Company in Sunnyvale, California, was responsible for designing, developing, and fabricating the support systems and assembling and testing all the major telescope components in the observatory. Perkin-Elmer Corporation in Danbury, Connecticut,

was responsible for designing, developing, and fabricating the Optical Telescope Assembly. NASA also engaged contractors to build the scientific instruments.

NASA selected a group of scientists to participate in the design and early operational phase of the project. Their charter was to define the observing plan for the telescope, establish scientific priorities, and organize operations to obtain the best results from this new research facility. During the two decades of telescope design and development activity, the scientific community has been formulating and refining this observing plan through a well-organized process of study groups, proposals, and peer review. The program continues to mature as new information from other astronomy missions influences the inquiries and objectives to be pursued with the Hubble Space Telescope.

In late 1983, as the telescope neared completion, it was renamed in honor of the American astronomer Edwin P. Hubble. Launch was tentatively scheduled and postponed several times into the late 1980's with telescope development problems and delays in the Shuttle program. During the long and eager wait for launch, time was well spent in additional ground tests, crew and operations team training, and science planning.

A "constellation" of NASA centers, European Space Agency affiliates, universities, research laboratories, industrial contractors, and their vendors in the United States and Europe participated in the development of the Hubble Space Telescope.





Guided Tour

of the Hubble Space Telescope

The Hubble Space Telescope is just over 13 meters (43 feet) long and 4 meters (14 feet) in diameter, about the size of a bus or tanker truck. Upright, it is a five-story tower; carried inside the Space Shuttle for the trip to orbit, it fills the payload bay.

The Hubble Space Telescope is made up of three major elements: the Optical Telescope Assembly, the focal plane scientific instruments, and the Support Systems Module, which is divided into four sections, stacked together like canisters:

Aperture Door and Light Shield: protecting the scientific instruments from light of the sun, Earth, and moon and also from contamination

Forward Shell: enclosing the Optical Telescope Assembly mirrors

Equipment Section: girdling the telescope to supply power, communications, pointing and control, and other necessary resources

Aft Shroud: covering the five focal plane instruments and the three fine guidance sensors.

Solar energy arrays and communications antennas are attached to the exterior shell. Doors allow astronauts to remove instruments and components from the equipment bays. Handrails and sockets for portable foot restraints attached to the external surface aid the astronauts in performing maintenance and repair tasks.

Space Telescope Vital Statistics

Length:	13.1 m (43.5 ft)
Diameter:	4.27 m (14.0 ft)
Weight:	11,000 kg (25,500 lb)
Focal Ratio:	f/24

Primary Mirror

Diameter:	2.4 m (94.5 in)
Weight:	826 kg (1,825 lb)
Reflecting Surface:	Ultra-low expansion glass covered by aluminum with magnesium-fluoride coating

Secondary Mirror

Diameter:	0.3 m (12 in)
Weight:	12.3 kg (27.4 lb)
Reflecting Surface:	Ultra-low expansion glass covered by aluminum with magnesium-fluoride coating

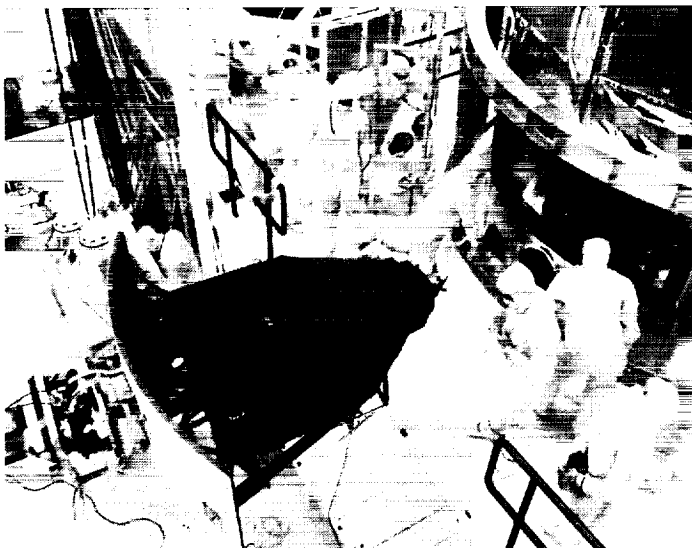
Systems

Optical Telescope Assembly
Support Systems Module
Focal Plane Science Instruments
Wide Field/Planetary Camera
Faint Object Camera
Faint Object Spectrograph
Goddard High Resolution Spectrograph
High Speed Photometer
Fine Guidance Sensors (for astrometry)

Data Rate: Up to 1 mbps

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The Hubble Space Telescope
during pre-flight testing



Wide Field/Planetary Camera Installation (Lockheed)

Wide Field/Planetary Camera

The Wide Field/Planetary Camera will observe larger sky areas and produce more data than the other instruments. This visible light camera operates in two modes: the planetary mode for exploring our own nearby solar system and the wide field

mode for the farther reaches of the universe.

In the wide field mode, the camera can make images of swaths of the universe for mapping distant galaxies and quasars. In four exposures, for example, it can photograph a giant galaxy in the Virgo cluster

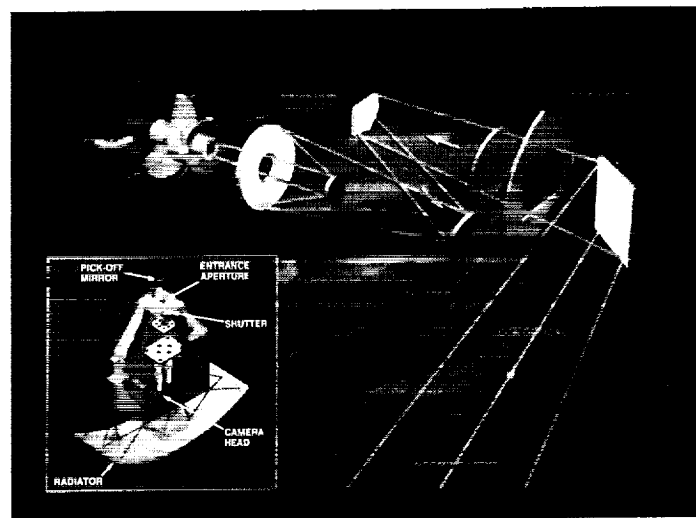
at an estimated distance of 60 million light years. The camera's field of view will contain dozens or even hundreds of galaxies located at distances of billions of light years. In this mode, the image clarity will be about 10 times sharper than typical photographs made at Earth-bound observatories.

In the planetary mode, this camera can photograph in a single exposure the entire face of any planet in our solar system, except Mercury, which is too close to the sun. Images of the outer planets Uranus and Neptune will be much better than those produced by ground-based optical systems. Pictures of closer planets, such as Jupiter, will resemble images from the Voyager spacecraft that approached the planet. Unlike images from ground-based telescopes, which can be made only at night when skies are clear, these images will be possible

on a routine basis; unlike Voyager images, which were snapshots frozen in time, the series of new images will reveal changes occurring over time, such as volcanic activity and atmospheric circulation.

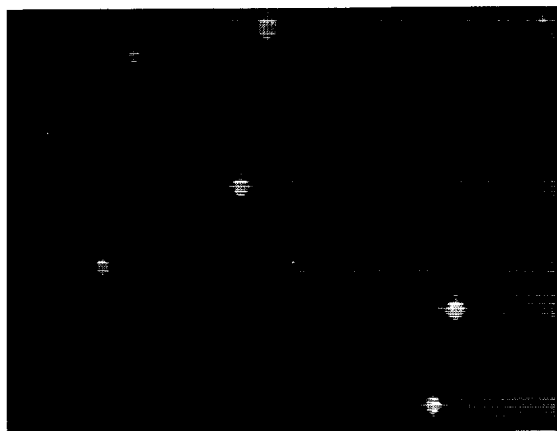
The Wide Field/Planetary Camera has 50 filters to sort radiation into different spectral bands. A star of the 16th magnitude (about 10,000 times fainter than the faintest stars visible to the naked eye) can be photographed in just one-tenth of a second. In longer exposures of 50 minutes or more, the camera can record stars of the 28th and 29th magnitude, about 40 times fainter than the dimmest objects routinely photographed with large ground-based telescopes. (From the ground, 24th magnitude can be detected in overnight exposures; on rare occasions, detection of 26th magnitude is possible.)

The Wide Field/Planetary Camera will observe larger sky areas and produce more data than the other instruments.



This simulated Wide Field/Planetary Camera image of a random starfield shows stars as faint as 31st magnitude in a 10-minute exposure.

(Space Telescope Science Institute)



Faint Object Camera

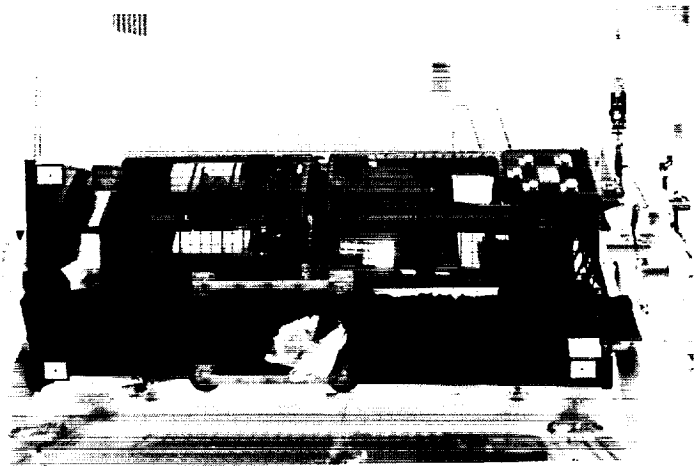
This instrument, built by the European Space Agency, obtains images of very faint objects, collecting information on objects at the greatest possible distances. It will detect stars as faint as the 28th magnitude and will easily pick out stars of the 24th magnitude, the limit of most large ground-based observatories. Many stars now considered dim will be readily seen.

An electronic image intensifier, capable of recording the arrival of individual photons, enhances feeble starlight and creates an image in the camera that is more than 100,000 times brighter than the image focused by the telescope mirror. Brighter wavelengths can be blocked by filters so that weaker ones can be recorded.

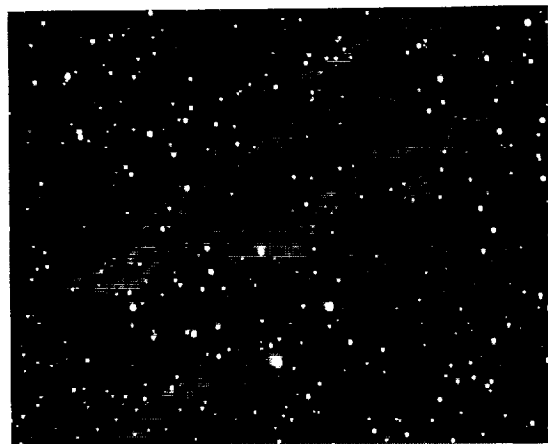
This camera is more sensitive in blue and ultraviolet light than the Wide Field/Planetary Camera, which is more sensitive to green and longer wavelengths. This instrument has sharper resolution, but the Wide Field/Planetary Camera covers larger areas. Astronomers can judge the merits of each camera and choose to use the one that best suits their

embedded in the gaseous filaments of nebulae in a matter of months.

The uniquely high resolution of the Faint Object Camera will enable us to distinguish fine details around the nuclei of active and distant galaxies, to search for black holes in nearby galaxies, and to study the surroundings of such very distant objects as quasars. Sensitive images with high resolution in the ultraviolet will show regions in distant galaxies where hot young stars are currently forming after collisions between galaxies. Some of the remarkable jets coming from the nuclei of galaxies, observed by radio telescopes, will be imaged for the first time in visible and ultraviolet wavelengths.



Faint Object Camera Installation (Lockheed)



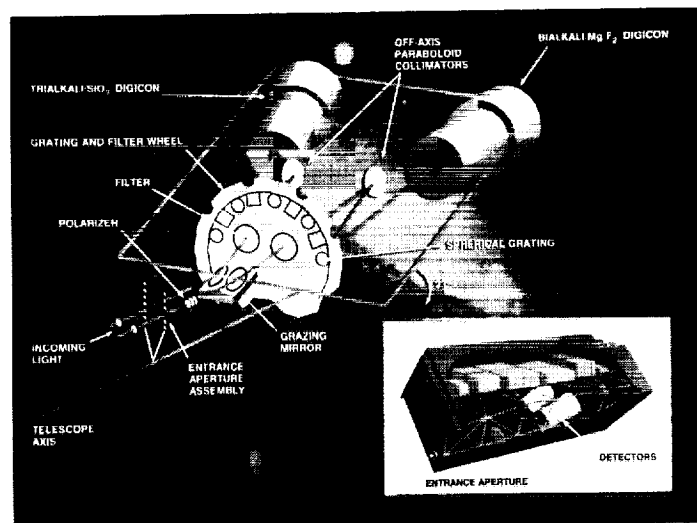
Vell Nebula (U.S. Naval Observatory)

The Faint Object Camera will detect stars in binary systems that are invisible from Earth because their light is lost in the observations. The camera will be able to observe stars that are too faint to be seen by the ground-based telescopes.

graph
strometry)

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The Faint Object Camera, built by the European Space Agency, will collect information on very faint objects at a greater distance than ever before possible.



Hubble Space Telescope Chronology

1918 2.5 m (100 in) Hooker Telescope began operations at Mt. Wilson Observatory in Pasadena, California

1923 Hermann Oberth published *Die Rakete zu den Planeträumen*, speculating on telescopes in orbit

1946 Lyman Spitzer wrote an advanced study, *Astronomical Advantages of an Extraterrestrial Observatory*

1948 5.1 m (200 in) Hale Telescope dedicated at Mount Palomar

1958 NASA established; U.S. civilian space program initiated

1962 National Academy of Sciences published *A Review of Space Research*; Iowa study group recommended a Large Space Telescope as a national goal

1966 National Academy of Sciences published *Space Research Directions for the Future*; Woods Hole study group also recommended a Large Space Telescope

1968 1st Orbiting Astronomical Observatory launched for ultraviolet studies of stars

1969 National Academy of Sciences published *Scientific Uses of the Large Space Telescope*

60's Growing support and endorsement in the scientific community; growing acceptance of space astronomy as worthwhile endeavor; confidence increasing with early scientific results and technology developments

1970 Feasibility Studies (Phase A) for 3-m Large Space Telescope
Large Space Telescope Steering Committee established

2nd Orbiting Astronomical Observatory

Preliminary Design (Phase B)
(1975: reduced to 2.4 m; European Space Agency involvement)

Development by prime contractors

International Ultraviolet Explorer First space telescope with "real-time" control

Astronauts began training with telescope mockup in Neutral Buoyancy Simulator

Work completed

Science Instruments delivered for testing at NASA;

Telescope Science Institute dedicated;

Telescope renamed Hubble Space Telescope;

Telescope Assembly delivered for assembly/integration

Telescope Operations Control Center dedicated

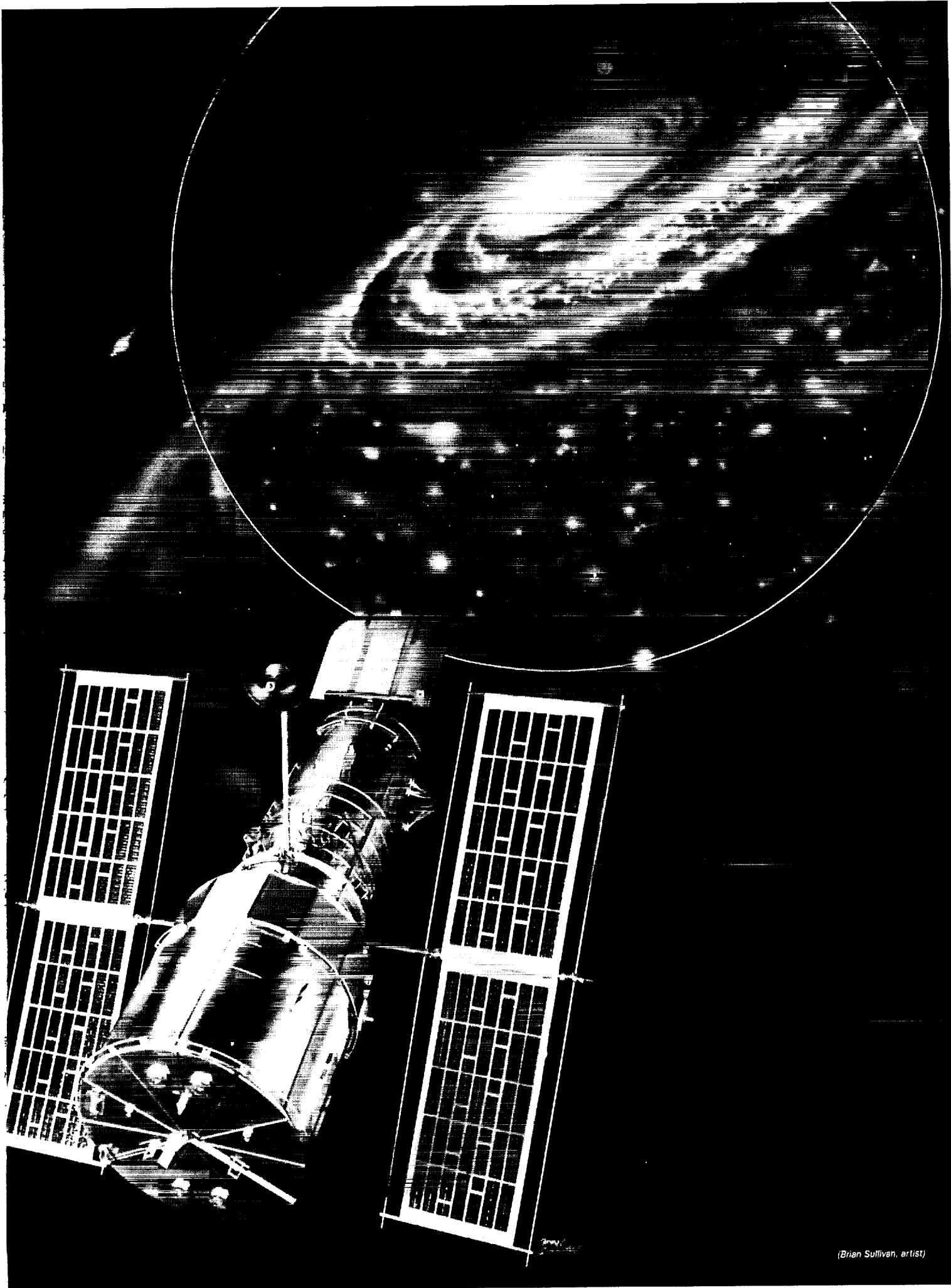
Launch of spacecraft completed

Proposals issued for observations

Delayed after Challenger accident; ground tests continued

End of opportunity for amateur observing time

Launch



(Brian Sullivan, artist)

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